DTU Library

Consequential life cycle inventory modelling of land use induced by crop consumption

Kløverpris, Jesper Hedal

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

Consequential Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption

PhD thesis 4.2010

DTU Management Engineering

Jesper Hedal Kløverpris
May 2010

DTU Management Engineering
Department of Management Engineering

Consequential Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption

Jesper Hedal Kløverpris

Industrial PhD Dissertation

Department of Management Engineering

Technical University of Denmark

Sustainability Development

novozymes

Consequential Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption
Industrial PhD Dissertation
Jesper Hedal Kløverpris
2010
ISBN: 978-87-90855-69-7
DTU Management Engineering
Institut for Planlægning, Innovation og Ledelse
Produktionstorvet 424
DK-2800 Lyngby
Denmark

Phone: +45 4525 4800
Mail: phd@man.dtu.dk

Print: Schultz Grafisk A/S

To Nanja

– for your support and patience

Preface

This dissertation describes the work performed during an industrial PhD project carried out at Novozymes A/S and the Department of Management Engineering at the Technical University of Denmark. The title of the project is *Consequential Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption*. The project was initiated in January 2005 and finalised in April 2008. In November and December 2006, the PhD project was temporarily interrupted by another project (exposure scenarios within the chemical EU regulation, REACH) carried out for Novozymes A/S. Furthermore, the Danish Institute of Product Development provided an extra 6 weeks pay from 29 May to 8 July 2007 because the preparations for the conference described in Chapter 8 were so time consuming that it was not possible to fit them within the frame of the PhD project alone.

The dissertation consists of a collection of 3 peer reviewed articles (Chapter 13) and a report that summarises and, in some cases, expands these articles. This is supplemented by a number of appendices with supplementary information and background data. Chapter 11 contains an overview of research stays and conference presentations.

Henrik Wenzel (previously associate professor at the Technical University of Denmark) was the university supervisor of the project until March 2007. Associate professor Michael Hauschild from the Department of Management Engineering at the Technical University of Denmark has been the university supervisor in the remaining part of the project. Director Karen Margrethe Oxenbøll from Novozymes A/S has been the company supervisor and Professor Anette Markan Reenberg from the Department of Geography and Geology at the University of Copenhagen has worked as a third party supervisor of the project.

The PhD project was defended in September 2008 at the Technical University of Denmark. Since then, only minor changes have been made to the dissertation. Most importantly, the present version of the dissertation contains the final version of Article 2 published in the International Journal of Life Cycle Assessment in January 2010.

Jesper Hedal Kløverpris

Acknowledgements

A wealth of people has contributed to the elaboration of the project in one way or another. I will not mention them all but I would like to thank Henrik Wenzel (University of Southern Denmark) for initiating the project and for our discussions. Also thanks to Michael Hauschild (Technical University of Denmark) for his guidance during the final stages. Furthermore, I am grateful to Karen Margrethe Oxenbøll (Novozymes A/S) for her support and encouragement from the beginning to the end. Thanks to Per Henning Nielsen (Novozymes A/S) for his guidance, interest, and detailed comments and to Kenneth Baltzer (Institute for Food and Resource Economics, University of Copenhagen) for excellent collaboration. Finally, thanks to Anette Reenberg (University of Copenhagen) for her guidance in the geographic world, Navin Ramankutty (McGill University, Montreal, Canada) for assisting with important GIS work and for hosting my stay at the University of Wisconsin in 2005, and Joyce Cooper (University of Washington) for hosting my stay in Seattle, also in 2005.

At last, I would like to thank Novozymes A/S for employing me during the project period and the Danish Ministry of Science, Technology, and Innovation for co-sponsoring the project.

Summary

Goal and Scope

The purpose of the present dissertation is to contribute to a more realistic inclusion of land use changes caused by crop consumption in LCA. The aim is to identify the mechanisms influencing the land use consequences of changes in crop demand and, on the basis of this conceptual analysis, present and demonstrate a method proposal for construction of marginal life cycle inventory (LCI) data for the land use induced by crop consumption.

The project focuses on changes in crop consumption, which are small compared to the total crop market. The geographical scope of the analysis is global and the temporal scope covers the time it takes for a change in crop demand to influence the global agricultural area. The technological scope concerns production with present agricultural technology but scenarios assuming demand driven technological development are also discussed.

Conceptual Analysis of Crop Production Mechanisms

The supply elasticity of crops expresses the change in production caused by a price change. This is one of the aspects of importance for the land use changes caused by changes in crop demand. Furthermore, it is important *how* the production of a given crop is changed. If increased crop production is achieved by displacement of other crops and/or livestock, this will lead to replacement of the displaced production elsewhere. Due to these displacement-replacement mechanisms, the effects of increased crop consumption trickle through the global agricultural system. In the end, increased crop production can only be achieved by expansion of the agricultural area or intensification of the existing production (higher yields per hectare).

Expansion caused by an additional increase in crop consumption must be seen in relation to the ongoing trend in land utilisation. If land utilisation is increasing, expansion is considered accelerated transformation of natural land. If land utilisation is falling, expansion is considered delayed relaxation of natural land being released to nature.

Intensification of crop production can be achieved by several means. These are divided in two categories. The first is called optimisation of production and concerns the adjustment of agricultural inputs to the field (fertilisers, pesticides, and irrigation) with the purpose of maximising profits. This is governed by prices on inputs and crops, and the relation between inputs and crop yields, which is characterised by diminishing returns[1]. In some countries, legal regulation of inputs to crop production limits the possibilities for obtaining the economically optimal yield.

The other intensification category is designated technological development and concerns the continuous improvement of mechanical aids, crop strains, and agricultural practices. This

[1] The more inputs applied to the field, the lower is the additional yield achieved per unit of input.

development is influenced by changes in crop demand but also driven by other factors. This aspect is therefore of importance for the land use consequences of increased crop demand.

Finally, the geographical location of a change in crop consumption influences the land use consequences because trade costs such as transport and tariff costs influence the prices of crops and thereby the ratio between intensification and expansion.

Modifying the GTAP Model and Database

The GTAP[2] Model is an economic general equilibrium model representing the global economy and its mechanisms. Many of the issues of importance for the land use consequences of increased crop demand can be handled by the model. To perform the desired estimation of land use changes, it is however necessary to modify the model and its database in the present project. As part of this procedure, the original number of regions and sectors in the database are aggregated so the world is divided in 22 regions, each with 15 sectors. There are eight crop sectors and four livestock sectors. Three other sectors represent the remaining part of the economy. Moreover, two agricultural land types are introduced in the GTAP Model, namely *cultivable land* with suitability for cropland and pastures, and *grazable land* with suitability for pastures but not crop cultivation. For each of the two land types in each of the 22 regions, a so-called land supply curve is implemented in the model to reflect the relationship between yet unutilised land and land price. Data on land availability and land utilisation is required for construction of the land supply curves. Land availability is estimated by subtracting human settlements and steep and protected areas from the total estimates of the two land types. Land utilisation is estimated by overlaying global maps of cultivable land and agricultural land use (cropland and pastures). This procedure is performed as a quantitative analysis in GIS[3] programme. Besides implementation of the land supply curves, the tariffs in the GTAP Database are updated. Furthermore, the inertia of global trade patterns is relaxed compared to the model's standard conditions. This inertia is stronger in the short term and the modification serves to reflect the long-term perspective usually applied in LCA. The influence of legal restrictions on inputs to crop production is not incorporated in the GTAP Model.

Simulating Increased Wheat Demand

The studied changes in crop demand are simulated with the modified GTAP Model by changing the buying preferences of the private households in the country of interest, which is referred to as the *scenario country*. This results in an increased wheat demand corresponding to 500,000 tonnes. This must be balanced by a corresponding decrease in the demand for other commodities in order to comply with the household budget constraint.

The output from the GTAP Model expresses relative changes in a wealth of variables, including crop production and land use changes. These changes are converted to physical

[2] Global Trade Analysis Project
[3] Geographical Information System

units via agricultural statistics and data on agricultural land use from the map used in the estimation of land type utilisation.

Results of the Economic Modelling

The modified GTAP Model is applied to estimate the changes in crop production and the expansion of the agricultural area caused by increased wheat demand in Brazil, China, Denmark, and the USA. Household consumption of one extra tonne of wheat in these four countries is estimated to result in a global increase in wheat production between 880 kg (Brazil) and 1100 kg (China). The net increase in wheat production (excluding the wheat used for seeds) is between 840 kg (Brazil) and 980 kg (China). Brazil and China cover most of the increase in wheat consumption by domestic production (84% and 97%, respectively) while Denmark and the USA obtain a large share from changes in trade flows (roughly half and two-thirds, respectively).

Intensification accounts for almost 30% of the increase in global wheat production caused by increased Danish consumption. This may be overestimated because restrictions on fertilisers are not accounted for. Intensification accounts for approximately 20% of the global increase in wheat production caused by wheat consumption in Brazil, China, and the USA.

Roughly 40% of the Brazilian increase in wheat production comes from displacement of other crops and livestock, and another 40% comes from expansion. In China, Denmark, and the USA, increased domestic wheat production is only achieved by displacement and intensification. In Brazil and China, the displacement of non-wheat crops is almost fully compensated for by intensification (92% and 78%, respectively). In Denmark and the USA, displacement of non-wheat crops is partly compensated for by intensification but mainly by changes in trade flows. The displacement of livestock on cultivable land does not have a significant influence on livestock production because some of the production is moved to the other land type (grazable land) and some of the land is substituted with capital and labour.

The global agricultural expansion caused by increased household consumption of one tonne of wheat in Brazil, China, Denmark, and the USA is, 2000, 260, 1700, and 3200 m^2, respectively. Roughly 70% of this expansion takes place on cultivable land, except in the Brazilian scenario where it is 90%.

Sensitivity analyses show that the results are valid for changes in wheat consumption up to one million tonnes per year. If demand driven technological development is included in the modelling, the estimated agricultural expansion is drastically reduced. However, these results only serve as an illustration due to lack of information on the exact relationship between demand and technological development. The results are sensitive to changes in the GTAP Database's so-called Armington elasticities, which express the inertia of global trade patterns as well as perceived and actual heterogeneity between domestic and foreign products.

Identifying the Biomes of the Areas Affected by Agricultural Expansion

To construct the land use life cycle inventory for wheat consumption, the natural potential vegetation, also designated the biome, is assigned to the areas affected by agricultural expansion. First, the ongoing trend in utilisation of the two land types (cultivable and grazable land) is assessed for the relevant regions based on agricultural statistics and historic crop maps. If the trend is positive, the estimated expansion in the relevant region is considered accelerated transformation. If it is negative, expansion is considered delayed relaxation. In both cases, the expansion is assumed to take place where the frontier between agriculture and nature is already moving. By locating these areas on a global map with 15 biome categories, the natural potential vegetation is assigned to the areas affected by expansion. This procedure is subject to some uncertainty and leaves room for improvement. However, it does give a simplified picture of the biomes likely to be affected by the modelled increase in wheat demand.

Land Use Life Cycle Inventory for Wheat Consumption

By combining the results from the economic modelling with the results from the biome analysis, the following land use LCI for consumption of one tonne of wheat is obtained (inconsistencies occur due to rounding). The numbers in the table indicate the areas of biomes affected by agricultural expansion followed by one year of agricultural occupation.

Biomes (natural potential vegetation)	Brazilian scenario	Chinese scenario	Danish scenario	US scenario
Savanna	230 m^2	53 m^2	300 m^2	590 m^2
Tropical evergreen forest	1,500 m^2	44 m^2	350 m^2	460 m^2
Boreal deciduous forest	57 m^2	49 m^2	97 m^2	850 m^2
Evergreen/deciduous mixed forest	25 m^2	14 m^2	200 m^2	160 m^2
Dense shrubland	29 m^2	10 m^2	260 m^2	140 m^2
Grassland/steppe	120 m^2	24 m^2	150 m^2	210 m^2
Open shrubland	43 m^2	38 m^2	170 m^2	480 m^2
Boreal evergreen forest	4 m^2	4 m^2	10 m^2	51 m^2
Rest (biomes unknown)	35 m^2	24 m^2	130 m^2	210 m^2
Total net expansion	2,000 m^2	260 m^2	1,700 m^2	3,200 m^2

A more detailed LCI distinguishing between the type of expansion (accelerated transformation and delayed release) as well as the land type (cultivable and grazable land) can also be constructed with the method presented. Furthermore, conversion of pastures to crop land (and vice versa) can be included in the land use LCI.

Perspectives

The methodology described and demonstrated in the present dissertation improves the link between land use LCI for crops and the subsequent land use LCIA (life cycle impact assessment) because it makes it possible to assess the environmental land use impacts actually occurring as a result of changes in crop consumption. The resulting expansion of the global agricultural area is modelled in combination with the resulting intensification of crop production. The ratio between marginal crop production achieved through expansion and intensification is thereby determined in a consistent and qualified manner. Furthermore, the construction of LCI data in an economic general equilibrium model like GTAP may inspire a new and more general approach to LCI modelling automatically accounting for price differences between alternatives compared in LCA. Finally, the work presented in the present dissertation has been used and is intended to be used as an input to the debate about the land use consequences of biofuels.

Resumé

Mål og afgrænsning

Formålet med denne afhandling er at bidrage til en mere virkelighedsnær inddragelse af de ændringer i arealanvendelse, som knytter sig til øget afgrødeforbrug, i livscyklusvurdering (LCA). Målet er at identificere de mekanismer, som styrer de arealmæssige konsekvenser af en øget efterspørgsel på afgrøder og, med afsæt i denne konceptuelle analyse, at præsentere og demonstrere et metodeforslag til konstruktion af en livscyklusopgørelse (life cycle inventory) af arealanvendelse fremkaldt af marginale ændringer i forbruget af afgrøder.

Projektet fokuserer på ændringer i afgrødeforbrug, som er små i sammenligning med det samlede marked for afgrøder. Den geografiske afgrænsning af analysen er global, og tidsmæssigt betragtes den periode, det tager, fra en ændring i efterspørgslen på afgrøder indtræder, til den fulde effekt har afsat sig på det globale landbrugsareal. Landbrugsproduktion antages som udgangspunkt at foregå med nutidig teknologi, men antagelser om efterspørgselsdrevet teknologisk udvikling diskuteres også.

Konceptuel analyse af mekanismerne i afgrødeproduktion

Udbudselasticiteten for afgrøder udtrykker produktionsændringen forårsaget af en prisændring. Dette er et af de aspekter, som påvirker ændringerne i arealanvendelse fremkaldt af ændringer i efterspørgslen på afgrøder. Desuden er det vigtigt, *hvordan* produktionen af en given afgrøde ændres. Hvis øget afgrødeproduktion opnås ved fortrængning af andre afgrøder og/eller husdyr, så vil dette føre til erstatning af den fortrængte produktion et andet sted. Effekten af øget afgrødeforbrug vil dermed vandre igennem det globale landbrugssystem på grund af disse fortrængnings-erstatnings-mekanismer. I sidste ende kan forøget afgrødeproduktion kun opnås ved ekspansion af det globale landbrugsareal eller intensivering af den eksisterende produktion (højere udbytter pr. hektar).

Ekspansion forårsaget af en ekstra forøgelse af afgrødeforbruget skal ses i relation til den igangværende tendens i udnyttelsen af land. Hvis denne er stigende, betragtes ekspansion som en accelereret transformation af natur. Hvis landudnyttelsen er faldende, betragtes ekspansion som en forsinket frigivelse af land til naturen.

Intensivering af afgrødeproduktionen kan foretages på adskillige måder. Disse deles i to kategorier. Den første kaldes optimering af produktionen og omhandler justeringen af gødning, pesticider og kunstvanding m.h.p. profitmaksimering. Denne justering styres af priserne på de nævnte input, afgrødepriserne og sammenhængen imellem inputforbruget og høstudbyttet, som er karakteriseret ved faldende afkast[4]. I visse lande er mulighederne for at opnå det økonomisk set optimale høstudbytte begrænset af lovmæssige reguleringer af brugen af gødning, pesticider og/eller kunstvanding.

[4] Jo større anvendelse af gødning, pesticider og kunstvanding, jo mindre stiger udbyttet per anvendt enhed.

Den anden intensiveringskategori betegnes teknologisk udvikling og omfatter den vedvarende forbedring af mekaniske hjælpemidler, afgrødesorter og landbrugspraksis. Denne udvikling påvirkes af ændringer i efterspørgslen på afgrøder, men drives også af andre faktorer. Dette aspekt er derfor af betydning for arealkonsekvenserne forårsaget af øget efterspørgsel på afgrøder.

Endelig påvirker den geografiske placering af ændringen i afgrødeforbrug de afledte arealkonsekvenser, fordi handelsomkostninger såsom transport- og toldomkostninger påvirker afgrødepriserne og dermed forholdet imellem intensivering og ekspansion.

Modificering af GTAP-modellen og GTAP-databasen

GTAP-modellen[5] er en økonomisk generel ligevægtsmodel, som repræsenterer den globale økonomi og dens mekanismer. Mange af aspekterne med betydning for arealkonsekvenserne afledt af øget afgrødeefterspørgsel kan håndteres af denne model. For at kunne foretage den ønskede estimering af ændringer i arealanvendelsen må modellen og den tilhørende database dog modificeres i dette projekt. Herunder aggregeres databasens oprindelige antal regioner og sektorer således at verden inddeles i 22 regioner, som hver har 15 sektorer. Der er otte afgrødesektorer og fire husdyrsektorer. Tre andre sektorer repræsenterer den resterende del af økonomien. Endvidere introduceres to typer landbrugsjord i GTAP-modellen, nemlig *dyrkbar jord* egnet til afgrødeproduktion og græsning samt *græsningsegnet jord*, som kan anvendes til græsning men ikke afgrødeproduktion. For hver af de to jordtyper i de 22 regioner introduceres en såkaldt jordudbudskurve i GTAP-modellen, som afspejler sammenhængen imellem mængden af endnu ubrugt jord og jordprisen. Konstruktionen af jordudbudskurverne kræver data for mængden af tilgængelig jord samt udnyttelsen af denne. Mængden af tilgængelig jord estimeres ved at fratrække menneskelig bebyggelse samt stejle og beskyttede områder fra de totale estimater for de to jordtyper. Udnyttelsen af jordtyperne estimeres ved at lægge et globalt kort med dyrkbar jord oven på et globalt kort over landbrugsarealer (arealer anvendt til hhv. afgrøder og græsning). Denne procedure er udført som en kvantitativ analyse i et GIS-program[6]. Udover implementeringen af jordudbudskurverne er toldsatserne i GTAP-databasen blevet opdateret. Desuden er trægheden i de globale handelsmønstre blevet løsnet i forhold til modellens standardtilstand. Denne træghed er stærkest på kort sigt og formålet med modificeringen er at afspejle det lange tidsperspektiv, som normalt anvendes i LCA. Den lovmæssige regulering af gødning, pesticider og kunstvanding er ikke indført i GTAP-modellen.

Simulering af øget efterspørgsel på hvede

De undersøgte ændringer i efterspørgslen på afgrøder simuleres med den modificerede GTAP-model ved at ændre de private husholdningers indkøbspræferencer i det relevante land, som betegnes *scenarie-landet*. Dette resulterer i en stigning i hvedeefterspørgslen svarende til

[5] GTAP: Global Trade Analysis Project
[6] GIS: Geografisk informations-system

500.000 tons. Dette skal modsvares af et tilsvarende fald i efterspørgslen på andre varer for at overholde husholdningernes budgetbegrænsning.

Output fra GTAP-modellen udtrykker relative ændringer i et væld af variable, herunder afgrødeproduktion og ændringer arealanvendelse. Disse ændringer konverteres til fysiske enheder via landbrugs-statistik og data for landbrugsarealer fra det kort, som også anvendes til estimering af de to jordtypers udnyttelse.

Resultater fra den økonomiske modellering

Den modificerede GTAP-model anvendes til at estimere ændringerne i afgrødeproduktion og ekspansionen af det globale landbrugsareal forårsaget af forøget efterspørgsel på hvede i Brasilien, Kina, Danmark og USA. Forøget husholdningsforbrug af et ton hvede i disse fire lande anslås at resultere i en global stigning i hvedeproduktionen på mellem 880 kg (Brasilien) og 1100 kg (Kina). Nettostigningen i hvedeproduktionen (ekskl. hvede anvendt som såsæd) ligger imellem 840 kg (Brasilien) og 980 kg (Kina). Brasilien og Kina dækker det meste af forbrugsstigningen for hvede via indenlandsk produktion (hhv. 84% og 97%), imens Danmark og USA skaffer en stor del via ændringer i handels-strømmene (hhv. ca. halvdelen og to tredjedele).

Intensivering dækker næsten 30% af den globale stigning i hvedeproduktionen forårsaget af den danske stigning i hvedeforbrug. Dette er muligvis overvurderet, fordi der ikke er taget højde for den lovmæssige regulering af gødning. Intensivering dækker ca. 20% af den globale stigning i hvedeproduktionen forårsaget af stigningen i hvedeforbrug i Brasilien, Kina og USA.

Ca. 40% af den brasilianske stigning i hvedeproduktionen stammer fra fortrængning af andre afgrøder og husdyr og andre 40% stammer fra ekspansion. I Kina, Danmark og USA opnås den forøgede indenlandske hvedeproduktion udelukkende via fortrængning og intensivering. I Brasilien og Kina kompenserer intensivering næsten fuldstændigt for hvedens fortrængning af andre afgrøder (hhv. 92% and 78%). I Danmark og USA kompenserer intensivering delvist for hvedens fortrængning af andre afgrøder, men kompensationen opnås i højere grad via ændringer i handels-strømmene. Fortrængningen af husdyr på dyrkbar jord har ikke nogen signifikant indflydelse på produktionen af husdyr, fordi en del af denne flyttes til den anden jordtype (græsningsegnet jord), og en del af jorden substitueres med kapital og arbejdskraft.

Ekspansionen af det globale landbrugsareal forårsaget af et tons ekstra forbrug af hvede i Brasilien, Kina, Danmark og USA er hhv. 2000, 260, 1700 og 3200 m^2. Ca. 70% af ekspansionen finder sted på dyrkbar jord med undtagelse af det brasilianske scenarium, hvor det er 90%.

Sensitivitetsanalyser viser, at resultaterne er gældende for ændringer i hvedeforbrug på op til en million tons om året. Hvis efterspørgselsdrevet teknologisk udvikling inkluderes i modelleringen, falder den estimerede ekspansion drastisk. Disse resultater tjener dog kun til illustration p.g.a. manglende information om den eksakte sammenhæng imellem efterspørgsel og teknologisk udvikling. Resultaterne er følsomme overfor ændringer i GTAP-databasens såkaldte Armington-elasticiteter, som udtrykker trægheden i de globale handelsmønstre så vel som faktiske og indbildte forskelle imellem indenlandske og udenlandske produkter.

Identifikation af biomer påvirket af ekspansion

For at konstruere livscyklusopgørelsen over arealanvendelse fremkaldt af ændringer i hvedeforbruget tilskrives den naturlige potentielle vegetation, også kaldet biomen, til de områder, som berøres af ekspansion. Først vurderes den igangværende tendens i udnyttelsen af de to jordtyper (dyrkbar jord og græsningsegnet jord) for den relevante region baseret på landbrugsstatistik og historiske kort over arealer anvendt til afgrøder. Hvis denne tendens er opadgående, betragtes den estimerede ekspansion i den relevante region som accelereret transformation. Hvis den er nedadgående, betragtes ekspansionen som forsinket frigivelse. I begge tilfælde antages ekspansionen at finde sted der, hvor grænsen imellem landbrug og natur allerede er i bevægelse. Ved at lokalisere disse områder på et globalt kort med 15 biomekategorier tilskrives den naturlige potentielle vegetation de områder som berøres af ekspansion. Proceduren er belagt med en vis usikkerhed og rummer muligheder for forbedring. Ikke desto mindre giver den et simpelt billede af de biomer, som sandsynligvis berøres af den modellerede stigning i efterspørgslen på hvede.

Livscyklusopgørelse for arealanvendelse fremkaldt af øget hvedeforbrug

Ved at kombinere resultaterne fra den økonomiske modellering med resultaterne fra biomeanalysen kan den følgende livscyklusopgørelse for arealanvendelse fremkaldt af øget hvedeforbrug opstilles (uoverensstemmelser forekommer p.g.a. afrundinger). Numrene i tabellen indikerer arealerne påvirket af ekspansion efterfulgt af et års dyrkning eller græsning.

Biomer (naturlig potential vegetation)	Brasiliansk scenarium	Kinesisk scenarium	Dansk scenarium	Amerikansk scenarium
Savanne	230 m^2	53 m^2	300 m^2	590 m^2
Tropisk stedsegrøn skov	1,500 m^2	44 m^2	350 m^2	460 m^2
Nordlig løvfældende skov	57 m^2	49 m^2	97 m^2	850 m^2
Stedsegrøn/løvfældende blandet skov	25 m^2	14 m^2	200 m^2	160 m^2
Tæt buskads	29 m^2	10 m^2	260 m^2	140 m^2
Græsland/steppe	120 m^2	24 m^2	150 m^2	210 m^2
Åbent buskads	43 m^2	38 m^2	170 m^2	480 m^2
Nordlig stedsegrøn skov	4 m^2	4 m^2	10 m^2	51 m^2
Rest (biomer ikke kendt)	35 m^2	24 m^2	130 m^2	210 m^2
Total netto-expansion	2,000 m^2	260 m^2	1,700 m^2	3,200 m^2

Det er også muligt at konstruere en mere detaljeret livscyklusopgørelse, som skelner imellem ekspansionstyperne (accelereret transformation og forsinket frigivelse) så vel som jordtype (dyrkbar jord eller græsningsegnet jord). Desuden kan konvertering af græsningsarealer til arealer med afgrøder (og vice versa) inkluderes i opgørelsen.

Perspektivering

Metoden beskrevet og demonstreret i nærværende afhandling forbedrer sammenhængen imellem livscyklusopgørelsen af arealanvendelse fremkaldt af øget afgrødeforbrug og den efterfølgende livscyklusvurdering af miljøpåvirkningerne (land use life cycle impact assessment / land use LCIA), fordi den muliggør en vurdering af de faktiske miljømæssige arealkonsekvenser, som finder sted som følge af ændringer i afgrødeforbruget. Den resulterende ekspansion af det globale landbrugsareal modelleres i kombination med intensivering af afgrødeproduktionen. Forholdet imellem marginal afgrødeproduktion opnået ved hhv. ekspansion og intensivering kan derved bestemmes på en konsistent og kvalificeret måde. Desuden kan konstruktionen af livscyklusopgørelsesdata (LCI data) i en økonomisk generel ligevægtsmodel måske inspirere til en ny og mere generel tilgang til modelleringen af livscyklusopgørelsesdata, som automatisk tager højde for prisforskelle imellem de alternativer, som sammenlignes i livscyklusvurdering (LCA). Endelig er det arbejde, som præsenteres i denne afhandling, blevet brugt i debatten omkring arealkonsekvenserne af biobrændsler, og hensigten er at fortsætte denne brug.

Abbreviations

This list contains the standard abbreviations used in the present dissertation.

GHG	Greenhouse gas
GTAP	Global Trade Analysis Project
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment

Glossary

This list contains a brief explanation of expressions as used in the present dissertation.

Accelerated transformation	Expansion type in regions with a growing agricultural area
Cultivable land	Land type with potential for rainfed cropland and pastures based on climate and soil constraints (Ramankutty et al. 2002b)
Delayed relaxation	Expansion type in regions with a falling agricultural area
Expansion	A net increase in the agricultural area compared to the ongoing trend (accelerated transformation or delayed release)
Grazable land	Land type with potential for rainfed pastures but not rainfed cropland
Intensification	Increasing the crop yields per hectare
Land type	Cultivable or grazable land depending on natural characteristics (soil and climate)
Land use	Cropland or pastures depending on the exploitation of the land
Marginal crop production	Aggregate change in crop production caused by a change in demand
Optimisation	Adjustment of inputs to crop production to achieve maximal profits
Scenario country	Country in which an increase in wheat demand is simulated
Technological development	Improvement of mechanical aids, crop strains, and agricultural practices

Table of Contents

1 Introduction 1
1.1 Objectives 2
1.2 Scope 2
2 State-of-the-Art in Land Use LCI Modelling 3
3 Conceptual Analysis of Crop Production Mechanisms 6
3.1 Supply Elasticity of Crops 6
3.2 Relationship between Crop Consumption and Land Use Changes 7
3.3 Displacement 7
3.4 Expansion of Croplands 7
3.5 Intensification of Existing Production 7
3.5.1 Optimisation of Production 8
3.5.2 Technological Development 8
3.6 Relationship between Demand and Technological Development 9
3.7 Significance of the Geographical Location of Crop Consumption 9
4 Economic Modelling of Marginal Land Use LCI Data for Crops 10
4.1 Modifying the GTAP Model and Database 10
4.1.1 Region and Sector Aggregation 11
4.1.2 Land Supply Curves 12
4.1.3 Introducing Two New Land Types in the GTAP Model 13
4.1.4 Modelling Physical Changes in Land Use in the GTAP Model 16
4.1.5 Adjustment of the Armington Elasticities 17
4.1.6 Updating the Tariffs in the Standard GTAP Database 18
4.1.7 Demand Driven Technological Development 18
4.2 Legal Regulation of Inputs to Crop Production 18
4.3 Simulating Increased Demand for Wheat in the GTAP Model 19
4.4 Conversion of the Output from the GTAP Model 19
4.5 Results: Crop Production 22
4.6 Results: Net Expansion of the Global Agricultural Area 25
4.7 Sensitivity Analyses 27
4.7.1 Linearity Check 27
4.7.2 Demand Driven Technological Development 27
4.7.3 Armington Elasticities 27
4.7.4 Alternative Cropland Area 28
4.8 Uncertainties in the Economic Modelling 29
5 Natural Potential Vegetation Affected by Agricultural Expansion 30
5.1 Assessment of Land Type Utilisation Trends 30
5.2 Locating Expansion on Cultivable Land in Multi Country Regions 31
5.3 Locating Expansion on Cultivable Land in Single Country Regions 31
5.4 Identifying Biomes Affected by Expansion on Cultivable Land 31
5.5 Locating Expansion on Grazable Land in Multi Country Regions 32
5.6 Locating Expansion on Grazable Land in Single Country Regions 32
5.7 Identifying Biomes Affected by Expansion on Grazable Land 32
5.8 Results: Biomes Affected by Regional Agricultural Expansion 33
5.9 Uncertainties in the Identification of Biomes Affected by Expansion 34

6 Land Use Life Cycle Inventory for Wheat Consumption 35
7 Discussion 37
7.1 Environmental Consequences of Intensification 37
7.2 Budget Constraints in LCA 38
7.3 LCI Data Modelled with General Equilibrium Models 39
8 Conference on Sustainability Assessment of Biofuels 41
9 Conclusions 42
9.1 Conceptual Analysis 42
9.2 Method Characteristics 43
9.3 Method Demonstration 43
10 Recommendations for Future Work 45
10.1 Land Supply Curves 45
10.2 Restrictions on Agricultural Inputs 45
10.3 New FAOSTAT Data 45
10.4 Alternative Shocks to Crop Demand 45
10.5 Other Models 46
10.6 Identification of Biomes Affected by Agricultural Expansion 47
10.7 Land use LCI Database 47
11 Research Stays and Conference Presentations 48
11.1 Research Stays 48
11.2 Conference Presentations 48
12 References 49
13 Article Collection 53
13.1 Article 1: LCI Modelling of Land Use – Part 1 55
13.2 Article 2: LCI Modelling of Land Use – Part 2 67
13.3 Article 3: Biomes Affected by Agricultural Expansion 87
14 Appendix 1: The Standard GTAP Model and Database 101
15 Appendix 2: Region Aggregation 105
16 Appendix 3: Sector Aggregation 110
17 Appendix 4: Adjustment of Cultivable Land 112
18 Appendix 5: Calculation Explanation 113
19 Appendix 6: Calculation Spreadsheet 124
20 Appendix 7: Adjustment of Potentially Grazable Land 125
21 Appendix 8: Grazable Land Available for Agricultural Production 126
22 Appendix 9: Double Demand (DD) Scenarios 127
23 Appendix 10: Technological Development (TD) Scenarios 128
24 Appendix 11: Double Armington (DA) Scenarios 129
25 Appendix 12: Quadruple Armington (QA) Scenarios 130
26 Appendix 13: Scenarios with Alternative Cropland Area 131
27 Appendix 14: Assumption 2 on Land Type Utilisation Trends 132
28 Appendix 15: Cropland Maps for Australia 133
29 Appendix 16: Cropland Maps for South America 134
30 Appendix 17: Cropland Maps for North America 135
31 Appendix 18: Cropland Maps for Asia 136
32 Appendix 19: Biome Map 137
33 Appendix 20: Conference on Land Use Implications of Biofuels 138

1 Introduction

Biotechnology is playing an increasingly important role in industrial as well as household processes. This includes the use of enzymes for a wealth of purposes. Enzymes are proteins with the ability to catalyse chemical reactions. They are found in all living beings and can also be produced for technical purposes by cultivation of microorganisms. Enzymes can be used in production of edible oils, leather, beer, textile, bread, paper, and numerous other products. In many applications, the use of enzymes reduces energy consumption, either directly or indirectly (Andersen and Kløverpris 2004). For instance, the addition of enzymes to laundry detergents makes it possible to reduce the temperature in laundry washing (Nielsen 2005). In addition to energy savings, many enzyme applications also reduce greenhouse gas (GHG) emissions, acidification, nutrient enrichment, and photochemical smog formation in comparison with their conventional alternatives (see e.g. Nielsen and Wenzel 2007, Skals et al. 2007, Nielsen et al. 2008, Thum and Oxenbøll 2008). However, the production of enzymes also involves the use of land because the microorganisms cultivated to excrete the enzymes must be supplied with crop-derived products such as sugars, starch, and protein (Nielsen et al. 2007a). On the other hand, some of the enzymatic applications have the potential to reduce agricultural land use because they increase the raw material efficiency of e.g. vegetable oil production (Andersen and Kløverpris 2004). In any case, shifting from a conventional process to an enzymatic process will affect the need for crops and thereby the demand for agricultural land. The question is where the changes in the agricultural area will occur. In some regions of the world, most or all of the potentially cultivable land is already being utilised (Bruinsma 2002) so this is not where agricultural expansion will be observed. On the other hand, changes in the demand for crops in these regions may affect the agricultural area elsewhere. In order to make a truly holistic, environmental assessment of enzyme applications, this aspect must be taken into consideration. In fact, this aspect is of importance for any life cycle assessment (LCA) involving changes in the use of crops, either directly or indirectly.

So far, land use research within the LCA community has mainly focused on *how* to assess the environmental impacts when land is affected, whereas less attention has been paid to the challenge of identifying *where* land is affected. Existing life cycle inventory (LCI) data for crops (Nielsen et al. 2007b, Nemecek et al. 2007) do not reflect the fact that whenever the demand for crops changes, the global agricultural area is likely to be affected somewhere along the frontier between agriculture and nature. In countries where all potentially available agricultural land is already being utilised, changes in crop demand is not likely to change the agricultural area at all. This means that changes in the crop demand in one country may have land use consequences outside of that country. In order to capture these effects in LCA, it is necessary to apply a consequential approach to the LCI modelling of crop data. In other words, it is necessary to model the marginal land use response to a change in crop demand. This includes an estimation of the change in the global agricultural area as well as a characterisation of the areas affected by this change. This PhD dissertation presents a methodological proposal for how to establish such information and how to use it in land use inventories for crops.

1.1 Objectives

The purpose of this industrial PhD project is to contribute to a more realistic inclusion of land use changes caused by crop consumption in LCA. Firstly, the aim is therefore to identify the mechanisms influencing the land use consequences of changes in crop demand. On the basis of this conceptual analysis, the goal is to present and demonstrate a method for construction of marginal life cycle inventory (LCI) data for land use induced by crop consumption. This method should take into account as many of the identified, relevant mechanisms as possible.

1.2 Scope

The main focus in the present PhD dissertation is on changes in crop consumption, which are small compared to the total crop market. However, some of the aspects discussed are also of relevance for large scale changes in crop demand.

As many crops are traded on the global market, the geographical scope of the analysis is global. The temporal scope is determined by the overall aim, namely to assess the changes in land use induced by changes in crop demand. In principle, this means that the temporal scope covers the time it takes for a change in crop demand to influence the global agricultural area. Regarding the technological scope, two different possibilities are considered. In the first one, production with present agricultural technology is assumed and, in the second one, increased demand is assumed to result in technological advances.

2 State-of-the-Art in Land Use LCI Modelling

Before describing some of the more advanced LCI modelling of land use performed to date, a few general remarks to inventory modelling are presented. Life cycle assessment of a given product is based on the inputs to and the outputs from the different stages in the product life cycle (see Fig. 1). To begin with, LCA was based on the *direct* inputs to the product life cycle. For instance, if electricity was used as an input to product manufacturing, all electricity technologies on the grid were included in the analysis taking into account the share of total electricity production provided by each technology. However, this approach is flawed. The reason is that LCA is a tool for decision support and thereby inherently concerns the study of changes (Wenzel 1998). If electricity consumption changes, only some of the technologies on the grid will be affected (Curran et al. 2005). It is therefore misleading to base the environmental assessment on average data for all the technologies on the grid. Instead, marginal data should be applied, i.e. data for the technologies affected by a change in demand. In fact, marginal data should be applied for any input in consequential LCA (Ekvall and Weidema 2004). This is quite obvious in a comparative LCA where the shift from one product to another is considered. But even when just one product is considered, there is an alternative to choosing that product, namely not choosing any product at all. In other words, it is also relevant to apply marginal data in LCA studies, which are not necessarily comparative. This means that it is necessary to consider whether the direct input to a product life cycle (see Fig. 1) is also the input representing the production affected by a change in demand.

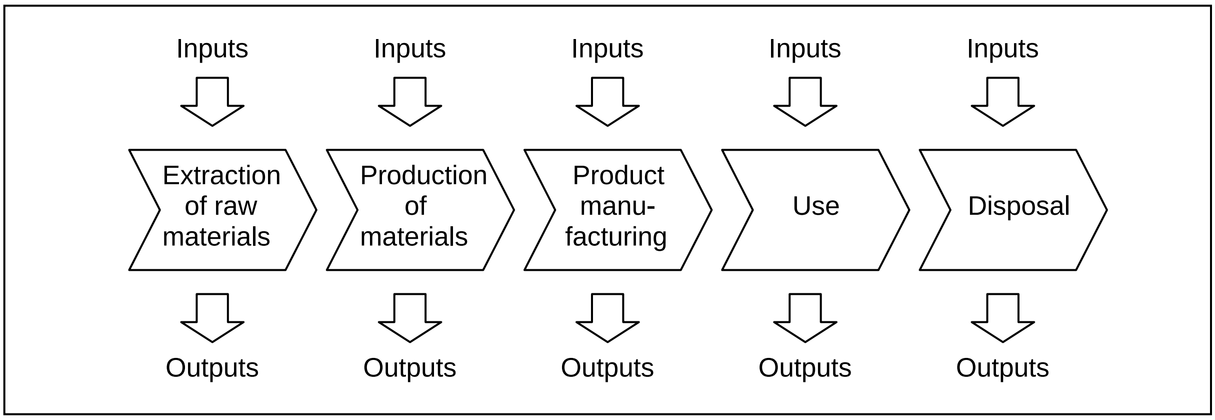


Fig. 1: Illustration of inputs and outputs during the life cycle of a product (Wenzel et al. 1997)

As discussed in the introduction, changes in crop consumption will affect the demand for agricultural land. More generally, any LCA involving changes in the occupation of land should consider the land ultimately affected. This is acknowledged by Lesage et al. (2007a, 2007b) who studied the environmental consequences of brownfield rehabilitation (the clean-up of urban, contaminated sites for the purpose of residential redevelopment) as an alternative to exposure minimisation (covering the site with clean soil and leaving it vacant). The results show that the environmentally preferable option is the rehabilitation. The reason is that exposure minimisation results in suburban development, i.e. indirect land use effects elsewhere. This illustrates the importance of including ultimate land use consequences in

LCA in order to arrive at the correct conclusion. Interestingly, Lesage et al. (2007b) assumed that brownfield rehabilitation conserves farmland (due to the avoided suburban development). This is in agreement with the fact that cities are often founded on fertile land (Ramankutty et al. 2002b). However, Lesage et al. (2007b) did not recognise that neither of the two alternatives studied has any significant effect on the global agricultural area. To be comparable, the two systems should result in the same functional output (in this case residential housing). If agricultural production is affected in one system (due to changes in the agricultural area) but not the other, the two systems are not comparable. The effect of farmland conservation, in this case in Canada, can therefore be considered neutral, because the net change in the global agricultural area can be assumed to be zero. Despite this inconsistency in the system modelling, the study by Lesage et al. (2007a, 2007b) is a prime example of consequential land use LCI modelling and its importance.

Schmidt (2007) also took the consequential approach to land use LCI modelling in his study of the environmental consequences of increased wheat demand in Denmark. Several scenarios were developed with different system delimitations. In scenario 3, which is based on the guidelines described by Ekvall and Weidema (2004), the increased Danish wheat demand was assumed to result in increased Danish wheat production at the expense of the marginal crop in Denmark, i.e. the crop affected by changes in production of other crops. According to Weidema (2003), the marginal crop in the EU is barley or wheat. Schmidt (2007) therefore assumed barley to be the crop displaced by increased Danish wheat production. As this results in a decreased supply of barley on the world market (and thereby higher barley prices), Schmidt (2007) sought to identify the marginal supplier of barley in order to determine the ultimate land use consequence of increased Danish wheat demand. The marginal supplier of barley is the supplier responding to a change in the barley price. Schmidt (2007) identified Canada as the marginal supplier of barley because this country is projected to have the largest absolute increase in barley production from 2005/06 to 2015/16 (FAPRI 2006). The ultimate land use change induced by increased wheat demand in Denmark was therefore assumed to be found in Canada. The rationale is that the supplier increasing its production the most must have the lowest production costs and thereby be more competitive than other suppliers. Unfortunately, there are some drawbacks to this procedure. To begin with, it does not consider the transport costs associated with the export of Canadian barley to the EU. Neither does it consider the trade costs in terms of the tariffs that must be paid at the EU border. In this context, it must be mentioned that Schmidt (2007) also developed scenarios in which the increased demand for wheat in Denmark was simply met within the borders of the EU. However, it is questionable whether it is reasonable to assume that just one country or region will respond to a change in crop demand. This is also acknowledged by Schmidt (2007). Furthermore, *if* just one supplier (in terms of a country or region) is assumed to be ultimately affected, it is questionable whether the identification of this supplier should be based on *absolute* changes in future production (as opposed to relative changes). This procedure excludes any small country as a potential marginal supplier. The reason is that the future increase in crop production is highly dependent on the existing area grown with crops. Even a small yield increase in a country with a large cropland area will result in a dramatic increase in production. It is therefore not surprising that Canada has the largest projected absolute increase in barley production because the country also has the fourth largest area of barley harvested (FAOSTAT 2007). If relative changes in production (i.e. the increase in projected production divided by the current production) were used as an indicator for the marginal supplier, the problem described would be solved and no country would be excluded up front. The marginal supplier could then be described as the supplier responding *the most* to outside changes, including changes in the demand and supply. Obviously, a farmer in a small country increasing production by 30% is more likely to represent the marginal supplier than a farmer, say in Canada, increasing production by 5%.

Meanwhile, there is another problem with using agricultural outlooks for the identification of marginal crop suppliers: The projected production increases are not necessarily demand driven. The production increases accruing from increased crop yields per hectare are likely to be driven, at least in part, by internal competition between farmers and by R&D activities (improvement of mechanical aids, agricultural practices, and crop strains) funded by public or private organisations (see Section 3.5.2). This is a problem because the marginal suppliers are, per definition, the suppliers responding to changes in supply and demand.

Despite the issues discussed above, the study performed by Schmidt (2007) is probably the best attempt to identify ultimate land use changes (and environmental consequences in general) caused by increased crop demand. The study is a major step forward and it identifies several issues, which are necessary to deal with. Among these issues, Schmidt (2007) discussed the challenge of determining, whether marginal crop production derives from intensification (higher yields per hectare), expansion of the agricultural area[7], or a combination. The present study presents a proposal for how to solve this problem as well as some of the other problems discussed above.

[7] Increased crop production achieved by expansion of the agricultural area is referred to as extensification (or just area) by Schmidt (2007). In the present study, the term expansion is used to designate a positive change in the agricultural area. The reason is that extensification may also be understood as the opposite of intensification, i.e. a reduction of the yield per hectare without any change in the area cultivated.

3 Conceptual Analysis of Crop Production Mechanisms

In order to model the marginal land use response to an increased demand for crops, it is necessary to obtain an understanding of the mechanisms governing crop production and crop markets. This chapter contains a conceptual analysis of these aspects, which is mainly a summary of Section 2 in Article 1 (Kløverpris et al. 2008a).

In the following, the expression *marginal crop production* is used to describe the aggregate change in crop production caused by a change in demand.

3.1 Supply Elasticity of Crops

In a consequential analysis, it must be considered whether the consumption of a certain amount of crops will lead to an equal increase in crop production or if the consumed crops will just not be available for another purpose. This depends on the supply elasticity of crops, i.e. the relative change in production (supply) per relative change in price[8]. On competitive markets with no constraints on production factors, long-term prices are not determined by demand but by the long-term production costs. This implies perfectly elastic supply or, in other words, increased consumption will be fully covered by increased production without any influence on prices or competing applications (Weidema 2003). The question is whether this holds true for crops. In 1798, demographer and political economist Thomas Malthus published 'An Essay on the Principle of Population' in which he suggested that the food production system is the limiting factor for population growth (Case and Fair 1999). Malthus simply believed that land would become a constrained production factor. This view was later challenged by Boserup (1965), who argued that mankind would always find new ways to produce food when it was necessary. Whereas Malthus believed that lack of land would eventually lead to food shortages, Boserup believed that this problem could be solved by intensified production brought about by technological development. The relationship between technological development and crop demand is important for identifying marginal crop production and thereby ultimate land use changes induced by crop consumption. This is discussed in Section 3.5.2. For now, it is only considered whether the long-term supply of crops is fully elastic at the present technological stage. As mentioned, this is only possible if there are no constraints on production factors. As for intermediate inputs to crop production (fertilisers, pesticides, etc.), this is believed to be the case (Abler 2003). The question is whether land is constrained as suggested by Malthus. According to Bruinsma (2002), the world is not approaching shortages of suitable agricultural land at the global level (despite regional shortages). However, new land might be less fertile than existing croplands. The marginal costs of crop production might therefore be higher than average production costs. This means that, although production factors in crop production (including land) can presently be considered unconstrained, the global supply of crops is not necessarily perfectly elastic. Another reason for this is that crop prices are also affected by transportation and trade costs.

[8] $(\delta Q_S/Q_S) / (\delta P/P)$

Finally, the agricultural sectors are dependent on capital and labour, which are also subject to constraints.

3.2 Relationship between Crop Consumption and Land Use Changes

The aggregate global crop demand is increasing due to several factors, including a growing global population, higher incomes in large Asian economies, and the use of crops for technical purposes, e.g. biofuels (OECD/FAO 2006). At higher demand for a specific crop, the production of this crop can be increased by *displacement* of other crops and livestock, *expansion* of the agricultural area, and *intensification* of the existing production of the relevant crop. Displacement will result in a reduced supply of other crops and/or livestock. This will lead to higher prices on these commodities and thereby provide an economic incentive for increased production elsewhere. This response to displacement is designated *replacement* and can also (like the production of the specific crop in increased demand) be achieved by displacement, expansion, and intensification. As long as replacement is achieved by more displacement, the effects of the initial change in demand will trickle through the agricultural system until replacement is only obtained by intensification and expansion. This chain of events is referred to as the *displacement-replacement mechanisms*. The sum of expansion taking place during the process described constitutes the total expansion of the agricultural area (ultimate land use) induced by the initial change in crop demand. The next three sections elaborate on the mechanisms for increasing the production of a given crop.

3.3 Displacement

As mentioned above, the production of a specific crop can be increased by displacement of other crops or livestock. However, some constraints apply to displacement because not all crops grow well on the same piece of land. Furthermore, crop rotation may be necessary to reduce the risk of diseases among the plants and, finally, farmers need to diversify their production in order to protect themselves against harvest failure for one or more crops.

3.4 Expansion of Croplands

Increased crop production can also be achieved by expansion of the agricultural area. If the price of land is low, expansion is likely to be more profitable than displacement and intensification. In this study, expansion is seen as a relative phenomenon in the sense that, if increased crop demand results in a reduced rate of cropland abandonment, this is considered a net expansion of the agricultural area (which would have been smaller in a business-as-usual scenario). In accordance with the terminology in the LCA land use literature (see e.g. Milà i Canals et al. 2007), such a reduced release of agricultural land is designated *delayed relaxation*. On the other hand, expansion in an area in which agricultural land use is already increasing is designated *accelerated transformation*.

3.5 Intensification of Existing Production

Intensification of crop production (i.e. increasing the yield per hectare) can be achieved in several ways. Some of them are directly related to the crop price and thereby indirectly to the demand. These are described below under the common term *optimisation of production*.

Other ways to increase crop yield per hectare can be summarised as *technological development*. This type of intensification is also described below.

3.5.1 Optimisation of Production

Higher yields per hectare can be achieved by increasing the application of fertilisers, pesticides, and irrigation. These inputs can also be used to increase the cropping intensity, which is defined as the ratio between harvested area per year and the area of arable land (Bruinsma 2002, p 379). The use of fertilisers, pesticides, and irrigation is subject to so-called diminishing returns, which means that the more of these inputs applied, the lower is the additional yield achieved (see Fig. 2A). The economically optimal application of fertilisers, pesticides, and irrigation depends on the prices of these inputs and the crop prices. The reason is that the optimum is determined by the largest difference between production costs (determined by inputs) and the value of production (yield multiplied by crop price). This is illustrated in Fig. 2B.

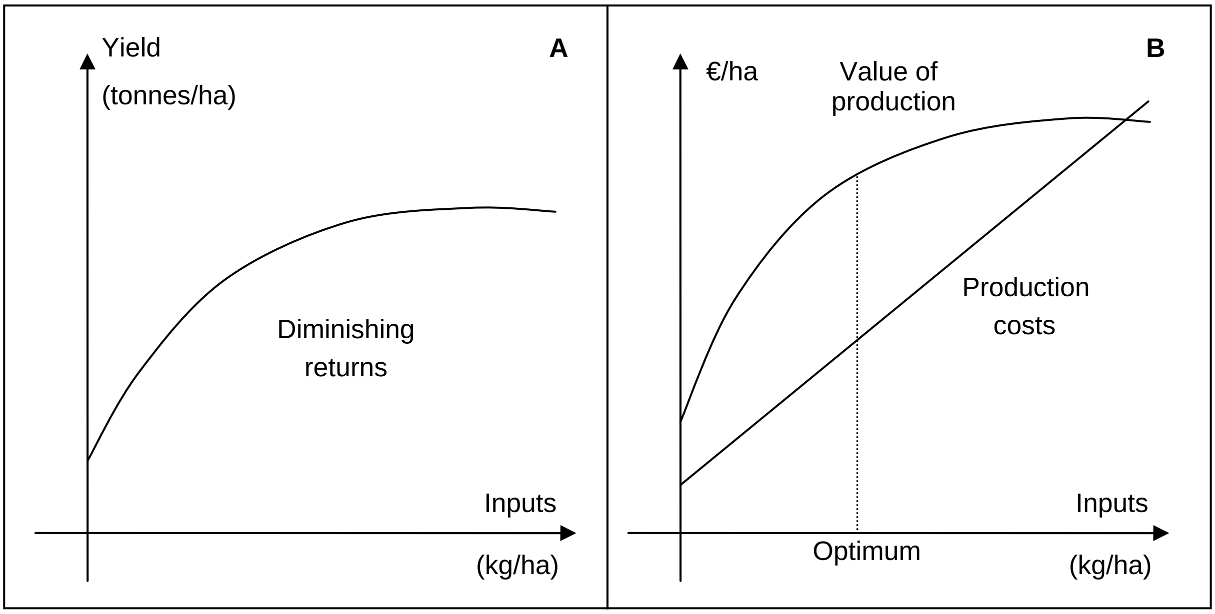


Fig. 2: Relationship between inputs and yield per hectare at a given technological stage (A) and the implications for profit optimisation (B). The optimum level of inputs is characterised by the largest difference between production costs and value of production (yield multiplied by crop price).

In some countries, e.g. in the EU, there are restrictions on the use of fertilisers (European Commission 2002). This means that the input of fertilisers may not always be determined by the economic optimum. Similar regional constraints may apply for pesticides and irrigation.

3.5.2 Technological Development

Higher yields per hectare can also be achieved by improving mechanical aids, crop strains, and agricultural practices. Adoption of such technological developments occurs automatically (regardless of changes in demand) as long as they result in lower production costs for the farmer. The technological development is controlled by either public or private institutions depending on the specific issue. Mechanical aids are typically developed by private companies whereas crop strain improvement is conducted by both private and public institutions, and the improvement of agricultural practices is mainly a public research area (Andersen 2006). Due to the different controllers of technological development, the drivers of technological development also differ. The development of mechanical aids is assumed mainly to be driven by internal competition between the suppliers of agricultural machinery. Private crop strain improvement is partly driven by internal competition between seed suppliers but changes in the demand for specific crops may influence the prioritisation of R&D efforts. In other words, crops in large demand will be the most likely candidates for further improvement. In case of threatening food shortages (potential unsatisfied demand), public funds may also be invested in the development of better crops. Such perceived threats may also influence public investment in the development of better agricultural practices. To sum up, intensification by technological development is largely driven by factors, which are not directly related to changes in crop demand. However, such changes may still have an impact on technological development, especially that concerning crop strain improvement.

3.6 Relationship between Demand and Technological Development

Marginal crop production can ultimately be achieved from expansion and intensification (as displacement is only an intermediate process). The ratio between the contributions from these two sources of increased production is obviously decisive for the land use induced by increased crop demand. The contribution from intensification depends on the extent to which technological development is demand driven. If increased demand is actually driving significant technological development, this will result in higher crop yields per hectare and thereby reduction of the share of marginal crop production derived from expansion. This illustrates the significance of the relationship between demand and technological development.

3.7 Significance of the Geographical Location of Crop Consumption

In consequential LCA, it is often assumed that the marginal supply of a product stems from one technology or one (type of) supplier in the market. This assumption is, however, too coarse for the global agricultural market, which is still characterised by tariff protection. This means that the crop suppliers affected by changes in crop demand depend on the geographical location of the change in consumption, which causes the change in demand. This is not just due to the trade costs but also due to the costs of transport.

4 Economic Modelling of Marginal Land Use LCI Data for Crops

As discussed in Chapter 3, the composition of marginal crop production (and thereby the location and area of the agricultural expansion caused by increased crop demand) is influenced by the following aspects.

- The supply elasticity of crops
- The displacement-replacement mechanisms
- The profitability of expansion compared to intensification depending on
    - land price
    - crop price
    - input prices
    - diminishing returns
- Regulation of inputs to crop production (fertilisers, pesticides, and water)
- The relationship between demand and technological development
- The geographical location of crop consumption (due to transport and trade costs)

Ideally, all these issues must be included in the LCI modelling of land use induced by changes in crop consumption. This requires a comprehensive modelling framework with global coverage. Several economic models qualify as candidates for such a framework. However, no perfect model encompassing all the issues mentioned above seems to be available. One of the apparently most well suited models for the analysis is the general equilibrium model called GTAP (Global Trade Analysis Project), which is a representation of the entire global economy. The model works in combination with the GTAP Database, which contains the information needed to run the model, e.g. production and trade flows and policy measures such as tariffs. The newest version of the GTAP Database (at the time of writing) corresponds to the year 2001 (version 6). It divides the world into 87 regions, each with 57 sectors (including eight primary crop sectors and four primary livestock sectors). Readers not familiar with the GTAP Model are referred to Appendix 1 for a more comprehensive introduction.

4.1 Modifying the GTAP Model and Database

Some of the aspects of importance for the modelling of land use induced by crop consumption are handled very well by the standard GTAP Model. The supply elasticity of crops is endogenously determined by the model based on the prices of primary production factors and intermediate inputs, and the displacement-replacement mechanisms are simulated in the sense that land can move from one sector to another depending on the most optimal use. Furthermore, the influence of transport and trade costs are accounted for by the model via the comprehensive information in the GTAP Database concerning international trade flows, trade agreements, and trade barriers. These advantages of the GTAP Model, along with its global coverage, constitute the main reasons for choosing this model. There are, however, also some aspects of the standard GTAP Model, which must be improved in order to use it for establishment of land use LCI data for crops. Several modifications of the standard GTAP Model are therefore performed.

4.1.1 Region and Sector Aggregation

In the land use modelling performed with the GTAP Model, the 87 regions in the standard GTAP Database (version 6) are aggregated to a total of 22 regions. These regions are listed in Table 1 and a full list of the countries in each region is available in Appendix 2. As Brazil, China, Denmark, and the USA are the countries in which an increase in wheat demand is modelled, these countries constitute separate regions (see Section 4.5). The aggregation of the remaining regions is considered a reasonable compromise between detail and overview[9]. However, more regions could be an advantage in some aspects (see Article 3: Kløverpris 2008).

Table 1: Codes for the 22 regions in the modified version of the GTAP Database

Code	Region	Code	Region
aus	Australia	per	Peru
xoc	Rest of Oceania	bra	Brazil
chn	China	xla	Rest of South America
xea	Rest of East and South East Asia	dnk	Denmark
jpn	Japan	xeu15	EU15 except Denmark
xsa	Rest of South Asia	eu12	EU12 (new member states)
ind	India	xer	Rest of Europe
can	Canada	xsu	Rest of Former Soviet Union
usa	USA	xme	Middle East and North Africa
mex	Mexico	xsc	South African Customs Union
xca	Rest of Central America	xss	Rest of Sub-Saharan Africa

Out of the 57 sectors in version 6 of the GTAP Database, the primary agricultural sectors are of special interest because they are closely related to the land use issue. These are therefore kept as separate sectors in the sector aggregation applied in the modification of the GTAP Database. The remaining regional sectors are aggregated in three groups, namely food processing, manufacturing, and services (see Appendix 3). The resulting 15 sectors are listed in Table 2.

[9] It should also be mentioned that the time it takes for the GTAP Model to complete a simulation increases exponentially with each extra region (or sector) in the database.

Table 2: Codes for the 15 sectors in the modified version of the GTAP Database

Code	Crop sectors	Code	Livestock and other sectors
pdr	Paddy rice	ctl	Bovine cattle, sheep and goats, horses
wht	Wheat	oap	Animal products not elsewhere classified
gro	Cereal grains not elsewhere classified	rmk	Raw milk
v_f	Vegetables, fruit, nuts	wol	Wool and silk cocoons
osd	Oil seeds	food	Food processing
c_b	Sugar cane, sugar beet	mnf	Manufacturing
pfb	Plant-based fibers	svc	Services
ocr	Crops not elsewhere classified		

4.1.2 Land Supply Curves

As previously described, the profitability of expansion compared to intensification depends on diminishing returns and the prices on land, crops, and inputs to crop production. Unfortunately, the issue of diminishing returns in crop production is not taken into account in the GTAP Model as the production structure in all sectors is modelled in the same way (see Appendix 1). This issue has not been solved during the work presented in this dissertation and it may result in an overestimation of the marginal crop production derived from intensification. As for the prices on crops and inputs to crop production, these are determined endogenously by the GTAP Model (depending on supply and demand). In fact, that is also the case for the price on land but some problems apply to this specific production factor. In the standard GTAP Model, the supply of land is normally fixed. This means that only intensification and displacement can be used to increase the production of a given crop, not expansion. Alternatively, land can be modelled as a production factor in endless supply but with a fixed price. The profitability of expansion compared to intensification can thereby be included in the modelling but still with a very poor representation of land markets, which does not consider regional land constraints (and their effects on land prices). To make the simulation of land markets more realistic, van Meijl et al. (2006) suggest the introduction of so-called *land supply curves*, which determine the regional relationships between land price and land supply (see Fig. 3). At low land utilisation, the supply of land is highly elastic, i.e. increased use only has a minor influence on the price (left side of the curve in Fig. 3). On the other hand, the supply of land is highly inelastic at high land utilisation, i.e. the price changes drastically even at small changes in the area being utilised (right side of the curve in Fig. 3).

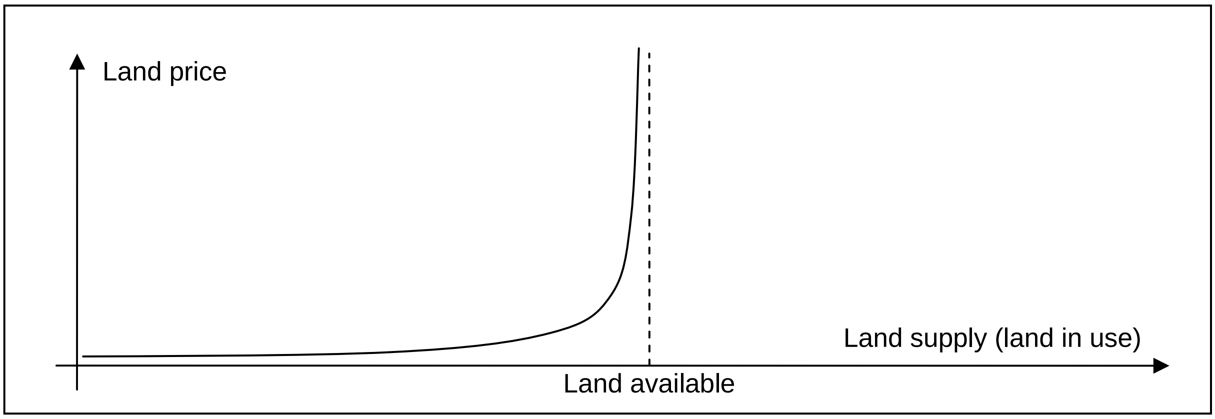


Fig. 3: General shape of a land supply curve. Adjusted from van Meijl et al. (2006).

The land supply curve is region specific and the shape of the curve (the sharpness of the bend) is determined by the monetary value of agricultural land in use (derived from the GTAP Database) and the current utilisation of land (for details, see Article 2: Kløverpris et al. 2008b). A main implication of the land supply curve is that crop production achieved by expansion will be relatively expensive in regions with a high utilisation of the available land area and therefore unlikely. In regions with full utilisation of the available area, expansion will be impossible.

4.1.3 Introducing Two New Land Types in the GTAP Model

In the standard GTAP Model, land is considered a homogenous production factor. To simulate the actual heterogeneity of land, it is modelled as a so-called sluggish production factor, which means that it does not move freely between sectors (see Appendix 1, Section 14.4). To improve the simulation of land heterogeneity, the homogeneous land type in the standard GTAP Model is replaced by two different land types. These are defined as follows:

- *Cultivable land* is land with potential for rainfed cropland and pastures based on climate and soil constraints. This definition is adopted from Ramankutty et al. (2002b).

- *Grazable land* is land with potential for rainfed pastures but not rainfed cropland.

Land supply curves are defined for these two land types in all of the GTAP regions. The necessary data on the value of land in use is obtained from the GTAP Database and the estimation of land availability and land utilisation is described below.

The availability of cultivable land is obtained by subtracting human settlements and steep and protected areas from the total estimates of cultivable land documented by Ramankutty et al. (2002b). This is graphically illustrated in Fig. 4. The global area of cultivable land assumed to be available for agricultural production is 30% lower than the unadjusted estimate of cultivable land (see Appendix 4). For Japan and the region xla (South America excl. Brazil and Peru), more than half of the cultivable land is assumed to be either protected, too steep for agricultural use, or occupied by human settlements. For further details, see Appendix 5 and 6.

The availability of grazable land is estimated by subtracting deserts, human settlements, and steep and protected areas from the area, which is not cultivable (see Fig. 4). The global area of grazable land assumed to be available for agricultural production is 45% lower than the unadjusted area of potentially grazable land (incl. deserts, see Appendix 7). For further details, see Appendix 5 and 6.

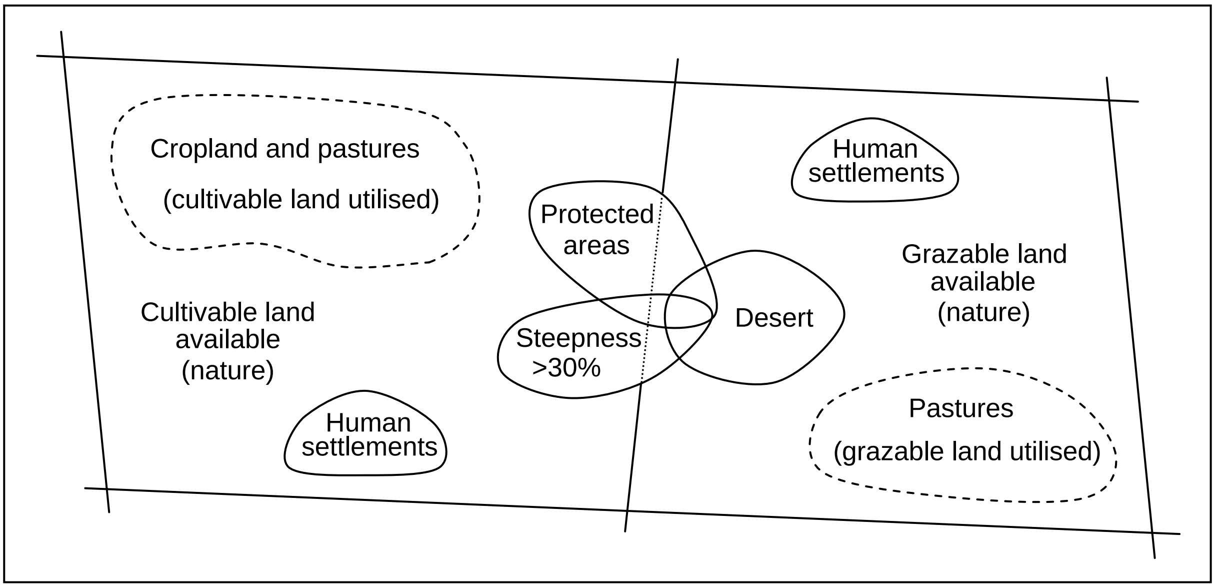


Fig. 4: Conceptual illustration of the areas accounted for in the calculation of land availability and land utilisation (data for the land supply curves). Deserts and steep and protected areas are assumed to be partly overlapping (see Appendix 5). These areas and human settlements are considered not to be available for agricultural production.

To calculate land type utilisation (input to land supply curves), the area of available land occupied by agricultural land use (cropland and pastures) is estimated country by country. This estimation is obtained by overlaying a global map of cropland and pastures (documented by Ramankutty et al. 2007) on a global map of cultivable land (documented by Ramankutty et al. 2002b). This procedure was kindly performed by Navin Ramankutty (McGill University, Montreal, Canada) and is conceptually illustrated in Fig. 5.

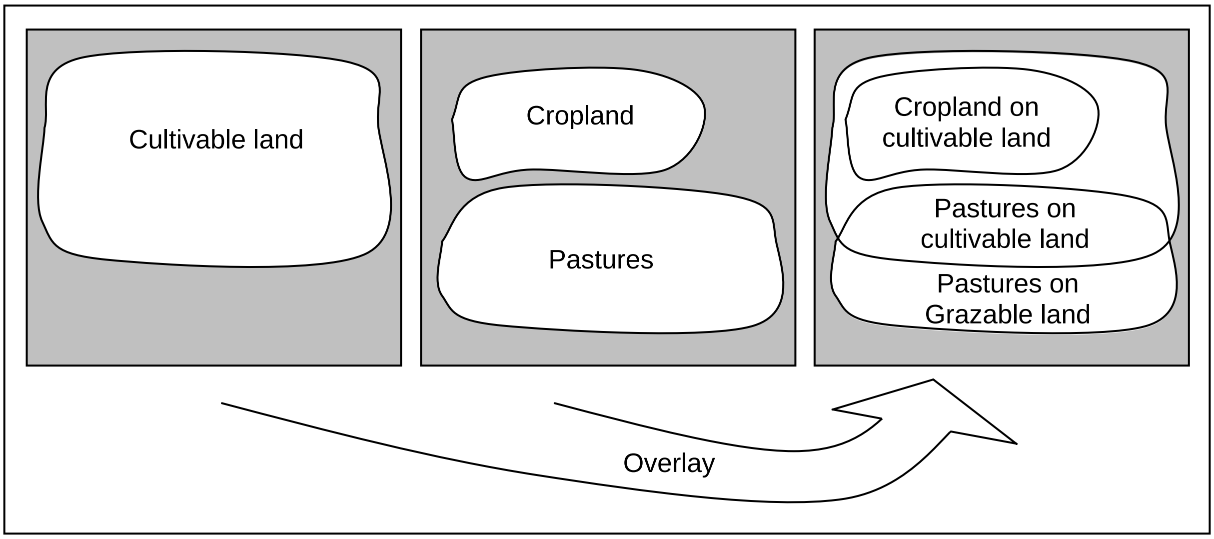


Fig. 5: Conceptual illustration of the overlay of the two maps showing cultivable land and agricultural land use, respectively.

The following areas are obtained from the overlay:

- Cropland on cultivable land
- Pastures on cultivable land
- Pastures on grazable land

Based on this information, the agricultural utilisation levels of the available areas of cultivable and grazable land are calculated[10] for basically all countries in the world (more than 200 in total). The data necessary for construction of the land supply curves is thereby obtained. Fig. 6 shows aggregated overlay data and estimated availability of cultivable land for the 22 regions applied in the land use modelling (see Table 1). Appendix 8 shows a similar figure for grazable land. For details, see Appendix 5 and 6.

[10] In some countries, crops are grown on grazable land, which is possible mainly due to irrigation. However, the modification of the GTAP Model only allows crops to grow on cultivable land. Cropland on grazable land has therefore been ignored in the calculation of grazable land utilisation. For some regions, this results in an underestimation of grazable land utilisation. This issue has been further discussed in Appendix 5.

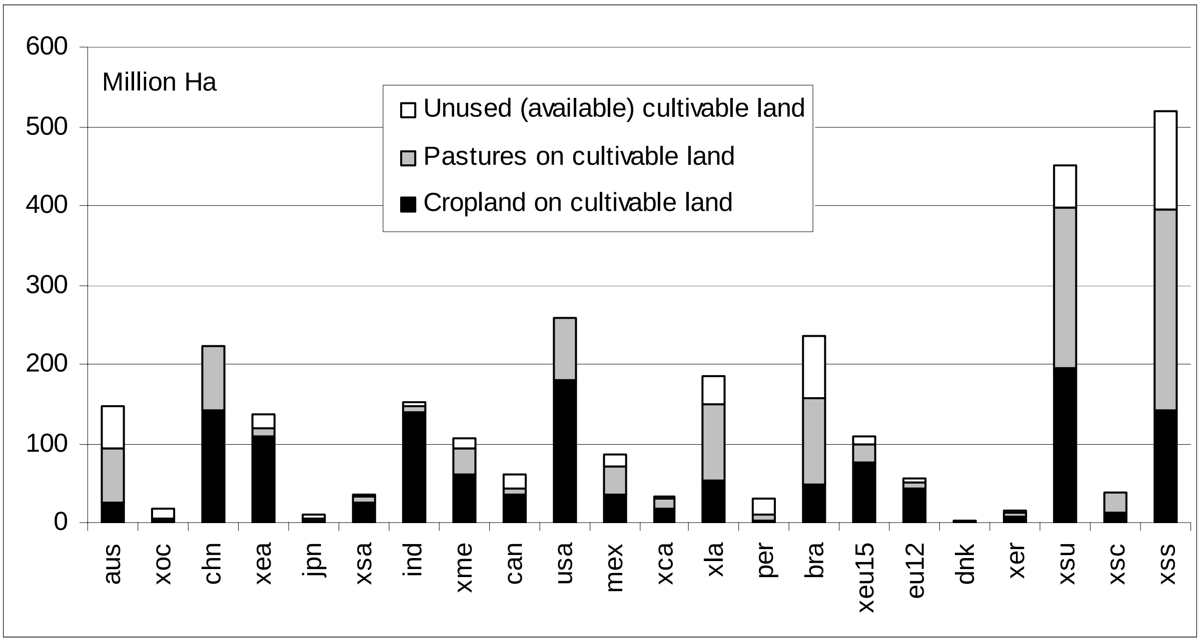


Fig. 6: Agricultural land use on cultivable land (overlay data) and estimates of unused cultivable land

4.1.4 Modelling Physical Changes in Land Use in the GTAP Model

In order to model physical changes in land use in the GTAP Model, some modifications are necessary. To begin with, the agricultural areas determined from the overlay described in Section 4.1.1 are distributed among the primary agricultural sectors in the GTAP Database. In the standard database, all eight crop sectors and all four livestock sectors use land. This is changed in the modification of the database so the cattle sector (ctl) and the raw milk sector (rmk) are the only livestock sectors using land[11]. The reason is that the two remaining livestock sectors, the wool sector (wol) and animal products not elsewhere classified (oap), only use minor areas of land. The direct land use in the wool sector is already accounted for by sheep in the cattle sector (ctl), and the oap sector mainly consists of livestock raised in stables and not on open pastures, e.g. pigs and poultry.

The distribution of land among the eight crop sectors and the two land dependent livestock sectors is performed as follows. 'Cropland on cultivable land' (obtained from the overlay data described in Section 4.1.1) are distributed among the eight crop sectors according to the distribution of area harvested in each sector (as reported by FAOSTAT 2007). 'Pastures on cultivable land' and 'pastures on grazable land' (also overlay data) are distributed among the two land dependent livestock sectors according to the value of land in these two sectors (given in the standard GTAP Database). The distribution procedure is conceptually illustrated in Fig. 7 and explained in detail in Appendix 5 and 6.

[11] Removing land from the wol and oap sectors requires an adjustment of the sectors' use of capital. This is briefly explained by Baltzer and Kløverpris (2008).

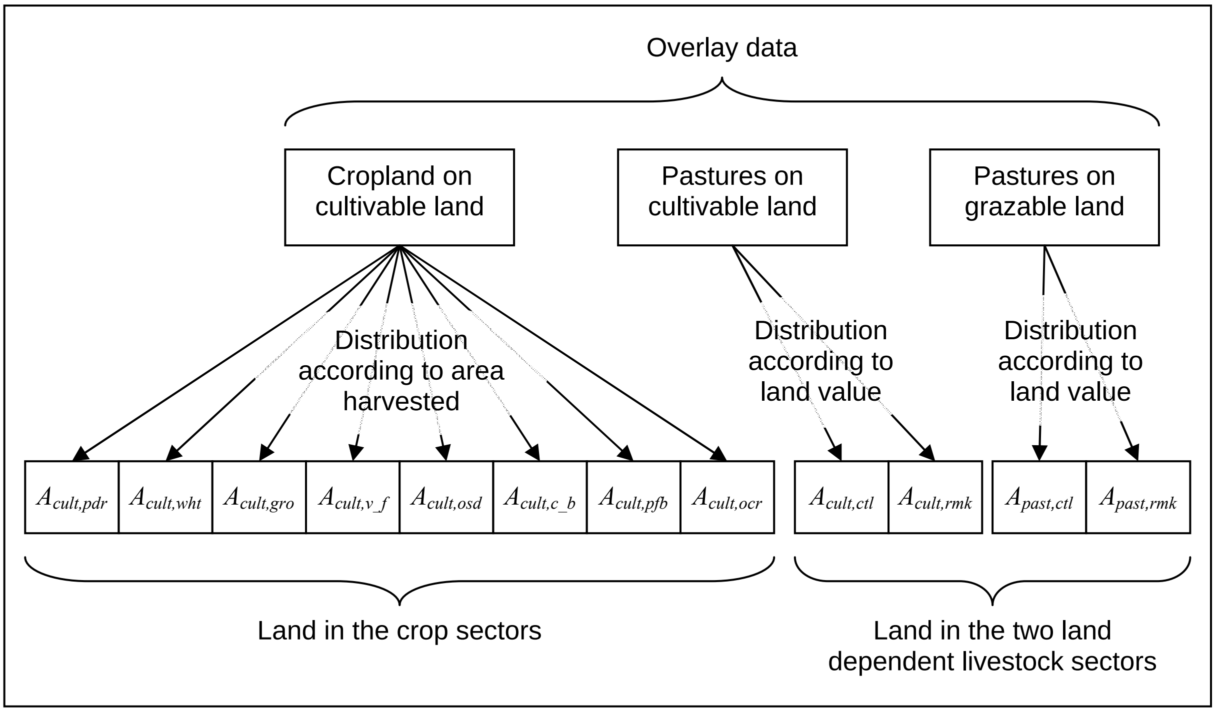


Fig. 7: Distribution of cropland and pasture areas (determined from overlaying maps of agricultural land use and cultivable land) among the primary agricultural sectors in the modified GTAP Database. The distribution according to area harvested is based on FAOSTAT (2007) and the distribution according to land value is based on the standard GTAP Database.

As mentioned in Section 4.1.1, land is modelled as a sluggish production factor in the GTAP Model to simulate the heterogeneity of land. This sluggishness is maintained for the two new land types (cultivable and grazable land) introduced in the modified version of the GTAP Model. However, the mathematical construction of the sluggishness has a disadvantage. The problem is that the sum of land use changes in the agricultural sectors (caused by a given exogenous shock) is not equal to the total change in agricultural land use. The mathematical explanation for this mismatch is explained by Baltzer and Kløverpris (2008) who propose the following solution to the problem: The change in land use in each sector (as reported by the GTAP Model) is interpreted as a change in productive capacity. This change is divided by a scaling factor, which is based on the physical land distribution demonstrated in the lower row of Fig. 7. The scaling factor provides a link between land value and land area and ensures compatibility between the GTAP output and the data used in the conversion of the output (see Section 4.4). In this way, the sluggishness of land (for both cultivable and grazable land) representing heterogeneity within each land type (and the displacement constraints mentioned in Section 3.3) is maintained and, at the same time, the sum of land use changes in each sector adds up to the total change in land use (measured in physical units). For a more detailed discussion of this issue, see Baltzer and Kløverpris (2008).

4.1.5 Adjustment of the Armington Elasticities

The Armington elasticities, representing the inertia of international trade patterns as well as actual and perceived heterogeneity of similar products from different regions (see Appendix 1), are doubled in the modification of the GTAP Database to reflect the longer time perspective usually applied in LCA (cf. the discussion of long-term production costs and supply elasticity in Section 3.1). The effects of increasing the Armington elasticities even further are investigated in the sensitivity analyses (see Section 4.7.3).

4.1.6 Updating the Tariffs in the Standard GTAP Database

As previously mentioned, the standard GTAP Database used as the starting point for the modifications described in this chapter represents the world economy in 2001. Several changes with important implications for world trade have occurred since then. For instance, China has entered into the WTO, the EU has been enlarged from 15 to 27 members, and the least developed countries have gained duty free access to the EU in accordance with the Everything But Arms agreement (European Council 2001). The resulting changes in tariff protection have been taken into account in the modification of the GTAP Database to better reflect the current flows in world trade (for details, see Baltzer and Kløverpris 2008).

4.1.7 Demand Driven Technological Development

In the standard GTAP Model, increased demand is not normally assumed to result in technological development but the model does allow for exogenous changes in technological development. To investigate the possible link between crop demand and technological development in crop production, the following mechanism is incorporated in the modified version of the GTAP Model: If the price of cultivable land in a region increases by two percent, the output per hectare of cultivable land increases with one percent (but only in the crop sectors). Due to lack of information, the magnitude of the effect of prices on productivity is arbitrarily chosen. The mechanism is only developed to get an impression of the effect of demand driven intensification on the expansion caused by increased crop consumption. The mechanism is therefore only applied in the sensitivity analyses concerning technological development.

4.2 Legal Regulation of Inputs to Crop Production

The standard GTAP Model does not operate with any legal restrictions on fertilisers or other inputs to crop production. This means that the model may overestimate the intensification response to increasing crop demand in regions with such restrictions. The initial ambition was to integrate the restrictions in the modified version of the GTAP Model. Meanwhile, it turned out to be extremely difficult to obtain a global overview of fertiliser restrictions (probably because such restrictions are not very common). The restrictions were therefore not included in the modelling. This section will, however, summarise the information retrieved on fertiliser restrictions during the PhD project.

In the EU, the nitrate directive imposes a limit of 170 kg organic nitrogen per hectare per year (European Commission 2002). In addition, artificial fertilisers may be applied but, at least for some countries, only within certain limits (Rauer 2007). According to Palliére (2007), Denmark has some of the strictest rules on artificial N fertilisation in the EU (apparently with negative consequences for wheat quality). The Danish limits on N fertilisation take the form of so-called ‘fertiliser accounts’, which define fertiliser quotas depending on crops, soil type, irrigation, and yield (Rauer 2007). It is worth noticing that these quotas are, per definition, a certain level below the economic optimum (see Fig. 2B). This means that even in Denmark, with its strict regulations, the crop price influences the inputs of artificial N fertilisers because there is no *fixed* limit but, in contrast, a limit which is defined *relative* to the economic optimum. Interestingly, it can be added that the application of N fertilisers in Denmark is predicted to increase slightly from now until 2016 (EMFA 2006). Some other countries in the EU have imposed taxes on N fertilisers (thereby reducing the economic optimum of application) in order to live up to the nitrate directive (Palliére 2007). Again, this does not decouple the level of N inputs from the crop price. Some information on N taxes, although not for the entire world, can be found in the database on environmental taxes (European Commission 2008).

4.3 Simulating Increased Demand for Wheat in the GTAP Model

After modifying the GTAP Model and Database (Section 4.1), the land use consequences of increased wheat consumption in Brazil, China, Denmark, and the USA are studied (one country at a time). The country in which the wheat demand is increased is referred to as the *scenario country*[12]. The increase in wheat demand is constructed by changing the buying preferences of the private households in the scenario country so that they increase their wheat consumption. In order not to violate the households' budget constraints, the preferences for other products than wheat are reduced correspondingly (same percentage change for all other products). The increase in demand is set at 500,000 tonnes. This change is large enough to be significant in the GTAP output but small compared to the total market. The results are thereby relevant for the marginal changes typically studied in LCA. Larger changes could, however, also be studied with the modified GTAP Model.

4.4 Conversion of the Output from the GTAP Model

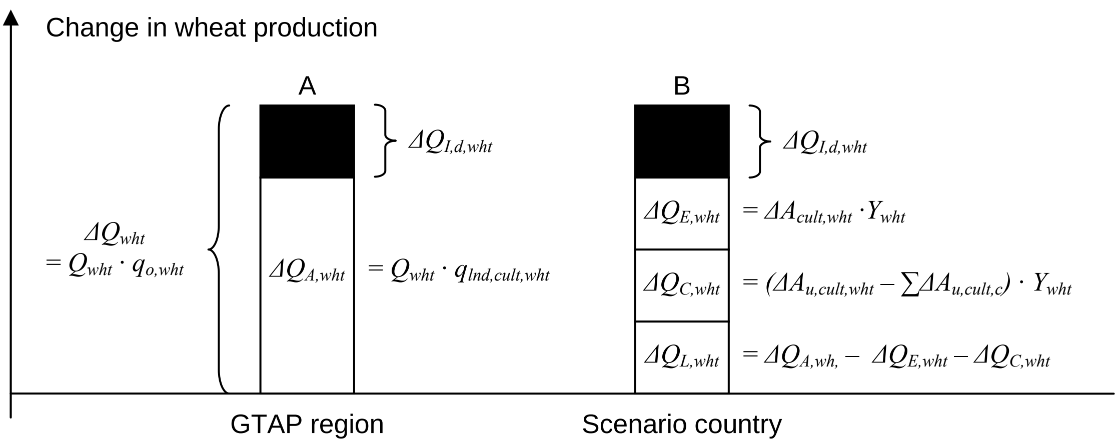
The output from the GTAP Model expresses the relative changes caused by the increase in wheat demand, e.g. changes in land use and crop production. Although the expansion of the agricultural area is of main interest in the present PhD project, the underlying changes in crop production are also studied to see how these comply with the conceptual analysis presented in Chapter 3. In an LCA perspective, this is highly relevant due to the environmental consequences of intensification (see the discussion in the introduction). This section describes how the GTAP output has been converted to production and land use changes measured in physical units.

The GTAP Model expresses changes in production and land use for each single crop sector. As it is the wheat demand which is increased, the changes in wheat production are studied independently. First, the full change in wheat production in each of the 22 GTAP regions is calculated by multiplying the relative production change (GTAP output: $q_{o,wht}$) with the wheat

[12] The term 'scenario *country*' is used because the changes in wheat demand studied in this PhD project are all placed in specific countries (as opposed to regions consisting of several countries). More generally, the term 'scenario *region*' could also be used.

production (Q_{wht} obtained from FAOSTAT 2007). The fraction of the total increase in wheat production achieved by an increase in the wheat area ($\Delta Q_{A,wht}$) is calculated by multiplying the relative change in land used by the wheat sector (GTAP output: $q_{lnd,cult,wht}$) with the wheat production (Q_{wht}). Wheat production from demand driven change in intensity ($\Delta Q_{I,d,wht}$) is calculated as the difference between total change in wheat production and wheat production from change in area. Details are given in Appendix 5 and 6, and a graphical overview is presented by the left bar (A) in Fig. 8.

The distribution of wheat production between change in respectively area and intensity (described above) is performed for all 22 GTAP regions. For the scenario country, the wheat production derived from area change is further broken down into production from expansion and production from displacement of respectively other crops and livestock. The details of these calculations are explained in Appendix 5 and 6, and a graphical overview is presented by the right bar (B) in Fig. 8.



ΔQ_{wht}	Total change in wheat production
$\Delta Q_{I,d,wht}$	Wheat production from demand driven change in intensity ($\Delta Q_{wht} - \Delta Q_{A,wht}$)
$\Delta Q_{A,wht}$	Wheat production from change in area
Q_{wht}	Initial production in the wheat sector (2001)
$q_{o,wht}$	Relative change in production in the wheat sector (GTAP output)
$q_{lnd,cult,wht}$	Relative change in cultivable land used in the wheat sector (GTAP output)
$\Delta Q_{E,wht}$	Change in wheat production caused by expansion
$\Delta Q_{C,wht}$	Change in wheat production caused by displacement of other crops
$\Delta Q_{L,wht}$	Change in wheat production caused by livestock displacement
$\Delta A_{u,cult,wht}$	Change in area in the wheat sector
$\sum \Delta A_{u,cult,c}$	Sum of area changes in all crop sectors
Y_{wht}	Initial annual yield per hectare in the wheat sector (2001)

Fig. 8: Graphical illustration of how the GTAP output is converted to changes in wheat production. A illustrates the calculations performed for all the GTAP regions while B illustrates the calculations performed specifically for the scenario country, i.e. the country in which the wheat demand is increased.

The production changes for each of the seven non-wheat crop sectors are also calculated (after the same principle illustrated in Fig. 8A). As many of these crops are partly displaced due to the increased wheat demand, the production from change in area is typically negative. This loss in production can be partly or fully outweighed by a change in intensity. To get an impression of this balance, the reduced production from change in area can be compared to the increased production from change in intensity. These data are available in Appendix 6. A more general picture can be obtained by comparing the aggregate reduced production of non-wheat crops from change in area ($-\Delta Q_{A,n\text{-}w}$) with the aggregate production of non-wheat crops from change in demand driven intensity ($\Delta Q_{I,d,n\text{-}w}$). This is done for all GTAP regions and graphically demonstrated in Fig. 9. Details can be found Appendix 5 and 6.

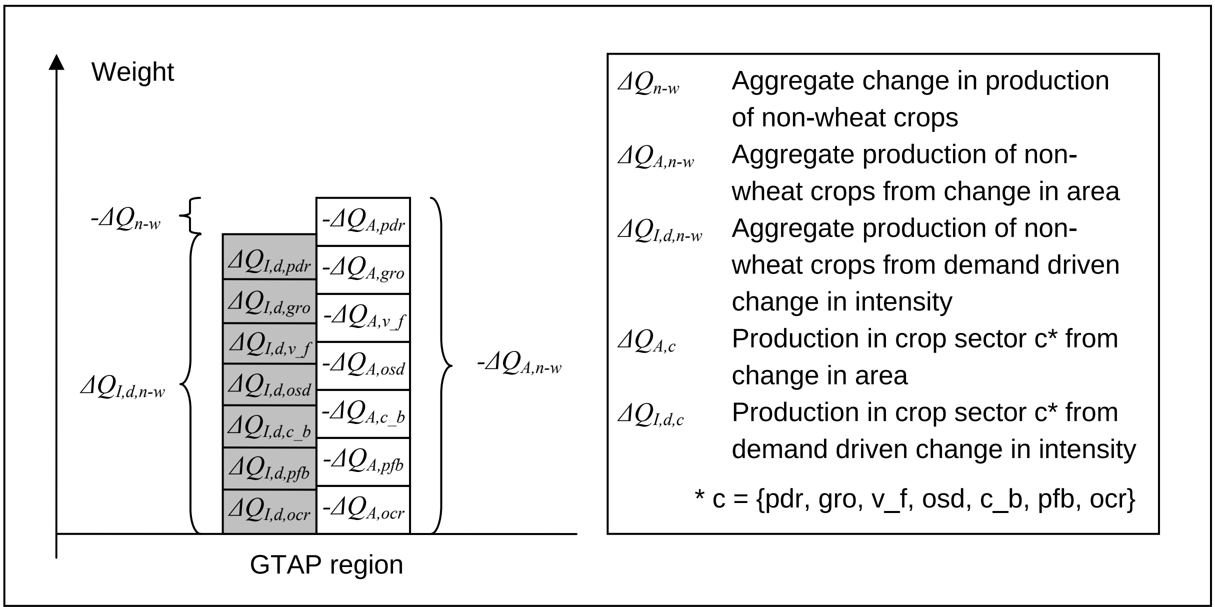


Fig. 9: Comparison of production of non-wheat crops from change in demand driven intensity ($\Delta Q_{I,d,n\text{-}w}$) and reduced production of non-wheat crops from change in area ($-\Delta Q_{A,n\text{-}w}$)

Changes in livestock production are also calculated but turn out to be of minor importance. Appendix 5 and 6 describe the calculation procedure.

The changes in production of crops and livestock lead to changes in the use of agricultural land and, due to the displacement-replacement mechanisms; the end result is expansion of the agricultural area on cultivable and grazable land (and intensification of agricultural production). The relative changes in the agricultural area are expressed by the GTAP outputs called $q_{o,cult,r}$ and $q_{o,graz,r}$, which are multiplied with the initial areas of respectively cultivable and grazable land in use ($A_{u,cult,r}$ and $A_{u,graz,r}$) to get the changes in physical units. For details, see Appendix 5 and 6.

4.5 Results: Crop Production

The consequences of increased wheat consumption in respectively Brazil, China, Denmark, and the USA are simulated in the modified GTAP Model. In the core scenarios, the standard Armington elasticities are doubled (see Section 4.1.5) but no demand driven technological development is assumed[13]. The wheat demand is increased by 500,000 tonnes (at the expense of other goods). The results are given per tonne of increased wheat consumption in the private households of the scenario country, i.e. the country in which the wheat demand is increased.

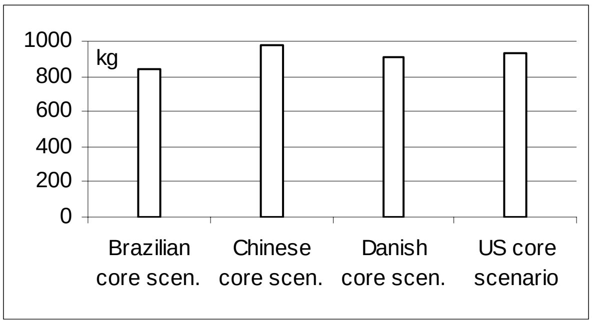


Fig. 10: Net change in global wheat production (excl. wheat seeds used by the wheat sectors)

The net change in global wheat production (excluding the wheat seeds consumed by the wheat sectors) is given in Fig. 10. The results show that when one extra tonne of wheat is consumed in the private households of the scenario country, most of it is provided by increased production but 2-16% is taken from other sectors or regions because the supply of wheat is not fully elastic. Furthermore, production of other crops is reduced because of displacement (see Fig. 12).

Fig. 11 shows the main changes in global wheat production. The results partly reflect the existing trade patterns of the world. The household consumption of wheat in Brazil and China is almost fully covered by domestic production and that is also the case for the simulated *increase* in consumption. However, the increase in wheat production is obtained in different ways by Brazil and China. Brazil has an estimated 78 million hectares of unused, available cultivable land (see Fig. 6 or Appendix 6). One-third of Brazil's increase in wheat production is therefore derived from expansion of the agricultural area. China, on the other hand, has full utilisation of both cultivable and grazable land and, consequently, the increased wheat production is only derived from intensification and displacement. As for Denmark and the USA, respectively 23 and 40 percent of the household wheat consumption prior to the change in wheat demand is covered by imports (according to the GTAP Database). Likewise, a large share of the *increase* in household wheat consumption (almost half and two-thirds, respectively) is covered by foreign production. Both Denmark and the USA have full utilisation of cultivable land, so none of the domestic increase in wheat production is achieved by expansion. On the other hand, Canada, which stands for more than 20% of the increased wheat production in the US core scenario, achieves more than half of this production by expansion. This reflects Canada's close trade relations to the USA, the short distance between the two countries, and Canada's estimated 18 million hectares of unused, available cultivable land (see Fig. 6 or Appendix 6).

[13] See Section 3.5.2, 3.6, and 4.1.7.

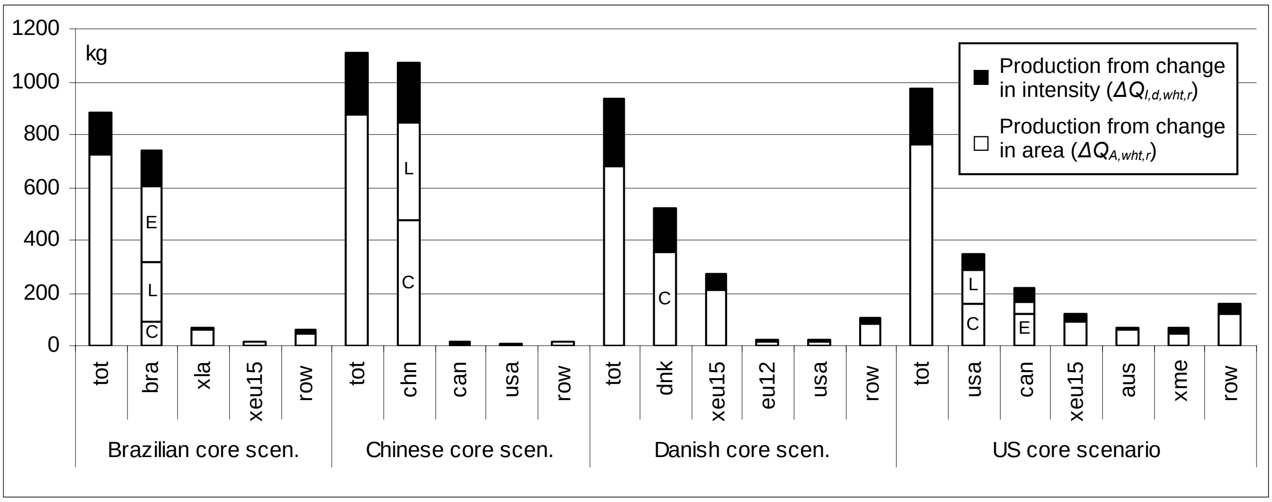


Fig. 11: Wheat production caused by consumption of one (additional) tonne of wheat in the four core scenarios. For the scenario countries, the change in wheat area is split into expansion (E), and displacement of other crops (C) and livestock (L). For Canada in the US scenario, production caused by expansion is also indicated. The regions with the lowest increase in wheat production are presented together as 'row' (rest of the world) and 'tot' stands for total.

The existing trade patterns have their current structure because consumers normally seek to satisfy their demands in the cheapest possible way. The main reason why household consumption of wheat in Brazil and China is mainly satisfied by domestic consumption is that this is the cheapest option under the given market conditions. Likewise, the main reason why a large share of the Danish and US household consumption of wheat comes from foreign sources is that this is economically optimal. It is therefore not surprising that the increased flows of wheat induced by increased consumption partly resemble the existing trade patterns. The most competitive suppliers before the change in demand will obviously also play a role after the change in demand.

Whereas the distribution of increased wheat consumption is highly related to the existing trade patterns, the availability of unused cultivable land seems to be less decisive for the suppliers responding to the increased wheat demand. There are two main reasons for this. First of all, the increased wheat production does not represent the final change in the global agricultural area. This is governed by the displacement-replacement mechanisms. Secondly, the price of land, which is partly depending on land availability (see Fig. 3), typically constitutes 20% or even less of the costs of crop production (according to the GTAP Database). This means that changes in the price of land only has a minor influence on crop production costs and thereby on the market prices of crops.

Although the availability of unused cultivable land has little influence on *where* wheat production is increased, it has a large influence on *how* wheat production is increased. This is reflected by the large share of wheat production achieved by expansion in Brazil in the Brazilian scenario and by Canada in the US scenario (see Fig. 11).

In the Danish core scenario, demand driven intensification accounts for almost 30% of the global increase in wheat production (see Fig. 11). In the scenario country itself, the increase in wheat yields is estimated at 1.7% or 120 kg/Ha[14]. This is likely to be somewhat overstated because the strict regulation of fertilisers in Denmark is not included in the modelling. In the remaining core scenarios, demand driven intensification accounts for roughly 20% of the global increase in wheat production (see Fig. 11) and the estimated changes in wheat yields in the scenario countries vary between 0.06% and 1.8% (or between 1 and 37 kg/Ha), which is considered reasonable in all cases.

A significant share of the increased wheat production in the scenario countries is achieved by displacement of other crops (see Fig. 11). This leads to a reduction of the supply of non-wheat crops. The resulting increase in prices creates incentives for intensification. In other words, the reduced production of non-wheat crops caused by the change in cultivated area is partly compensated for by change in intensity. Fig. 12 shows this balance as well as changes in the production of non-wheat crops in other regions than the scenario countries.

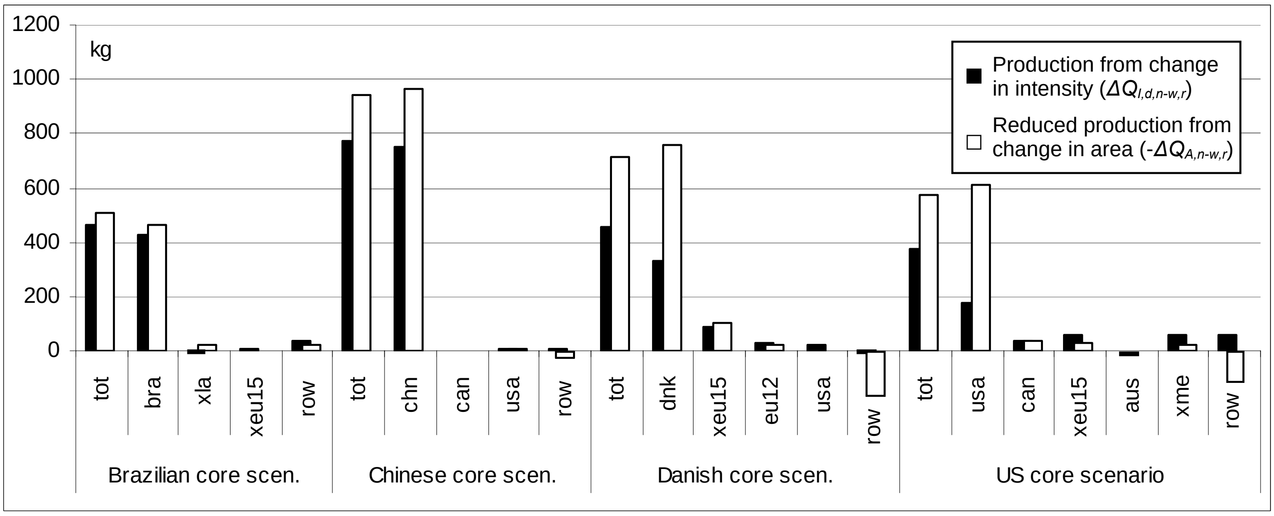


Fig. 12: Production of non-wheat crops (n-w) caused by consumption of one (additional) ton of wheat in the scenario countries. Note that the white bars indicate *reduced* production so the net change in production is the difference between the black bars and the white bars. The regions not mentioned explicitly are presented together as 'row' (rest of the world) and 'tot' stands for total.

It is only in the scenario countries that there is a direct connection between the wheat production from displacement of other crops (see Fig. 11) and the reduction of other crops from change in area (black bar in Fig. 12). The reason is that, due to the displacement-replacement mechanisms, the changes in non-wheat crop areas outside the scenario country are not necessarily caused by a larger wheat area alone but may also have to do with increased production of other crops caused by a decrease in the exports of these crops from the scenario country. Appendix 6 shows all changes in crop areas for every single crop and livestock sector in every single region. Note also, that the reduction of non-wheat crop production in the rest of the world (row in Fig. 12) is negative in three of the scenarios. This indicates that the

[14] For a discussion of the uncertainties related to the yield calculations, see Appendix 5.

area grown with non-wheat crops is actually increasing. This shows how an increased demand for a specific crop, via the displacement-replacement mechanisms, can lead to increased production of other crops achieved by expansion of the relevant crop areas in countries far away from the scenario country (in terms of trade relations).

Fig. 12 shows large differences in the scenario countries' domestic compensation for displacement of non-wheat crops. In Brazil and China, intensification compensates for respectively 90 and 80 percent of the displaced non-wheat crops and the global compensation levels are more or less the same. In Denmark and the USA, the domestic compensation level is 43 and 28 percent, respectively. The reason is that it is cheaper for Denmark and the USA to compensate for the displacement via trade than to intensify production. This means that the compensation for the reduced production is spread over a larger geographical area and therefore the global compensation level is lower in these two scenarios than in the Brazilian and Chinese scenarios.

Although significant areas of pastures are displaced by wheat production in three of the scenario countries (see Fig. 11), the global production of livestock is not changed significantly. The reason is that the displacement of livestock on cultivable land is partly compensated for by substitution with grazable land, capital, and labour. It is therefore found to be reasonable to exclude this aspect.

4.6 Results: Net Expansion of the Global Agricultural Area

The changes in crop and livestock production caused by the increased demand for wheat lead to changes in the global agricultural area. The total change is, however, highly dependent on where the increased wheat consumption takes place (see Fig. 13). The results for expansion of the agricultural area are also given per tonne of increased wheat consumption in the private households of the scenario country. In the Brazilian core scenario, the global expansion of the agricultural area is roughly 2000 m^2 of which three-quarters occur in Brazil itself due to the increased domestic wheat production. In the Chinese core scenario, the global agricultural expansion is only 260 m^2, which are distributed over several regions. This modest expansion (compared to the other scenarios) is explained by the high Chinese wheat production and the high compensation for displacement of non-wheat crops in China (see Fig. 11 and Fig. 12). These aspects minimise the land use consequences in the rest of the world. In the Danish and US core scenarios, the global expansion is roughly 1700 and 3200 m^2, respectively. This is spread over several regions because the increased wheat production takes place in many countries and because displacement of non-wheat crops in the scenario countries is partly compensated for by trade.

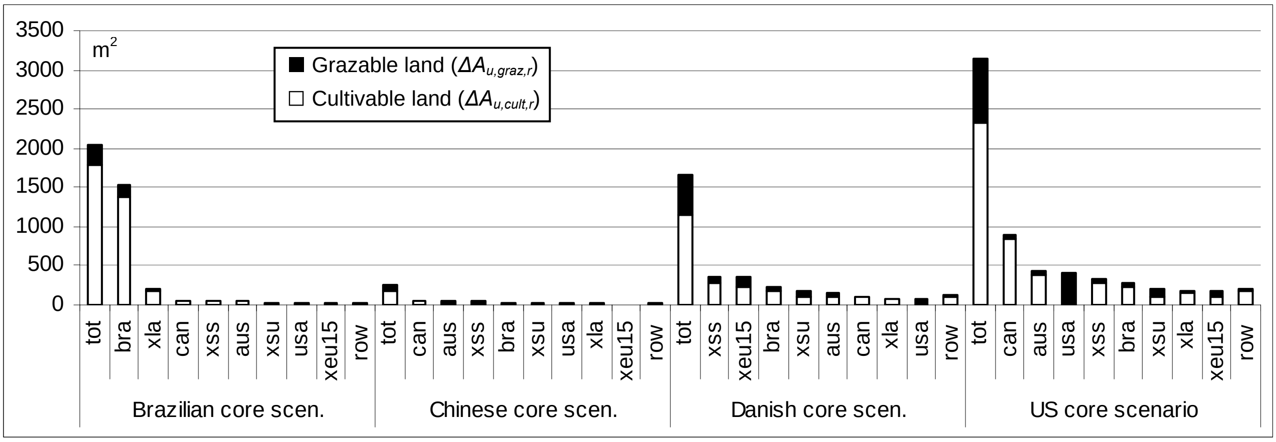


Fig. 13: Net expansion caused by consumption of one (additional) ton of wheat in the scenario countries. The regions with the lowest net expansion are presented together as 'row' (rest of the world) and 'tot' stands for total.

Most of the global expansion occurs on cultivable land but up to 30 percent takes place on grazable land, mainly because the increased crop demand pushes livestock from cultivable land to grazable land (conversion of pastures to cropland and nature to pastures).

Fig. 14 compares the reciprocal wheat yields in Brazil, China, Denmark, and the USA with the global expansion induced by wheat consumption in these four countries. If the increased household consumption were covered solely by displacement in the scenario countries, the reciprocal yield would express the area of other crops and/or livestock displaced. The expansion induced by wheat consumption can be seen as the result of this displacement.

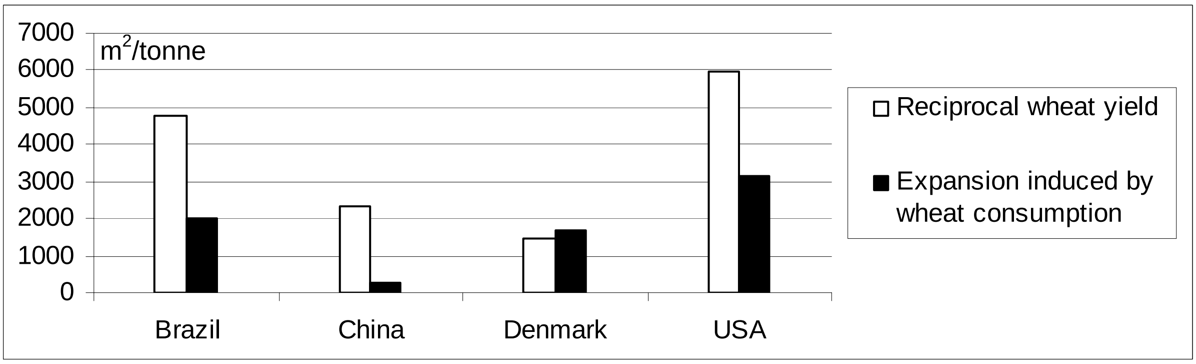


Fig. 14: Comparison of reciprocal wheat yields and expansion results from the core scenarios

4.7 Sensitivity Analyses

Several sensitivity analyses are performed to investigate the results' dependency and the size of the change in wheat demand, the influence of demand driven technological development, changes in the Armington elasticities, and the estimation of the global cropland area.

4.7.1 Linearity Check

In the Double Demand (DD) scenarios, the simulated increase in wheat demand is doubled (one million tonnes) to see if this changes the net expansion given per tonne of wheat consumed in the private households of the scenario country. The results show only minor variations compared to the core scenarios (less than 3%). It is therefore concluded that the results from the core scenarios are valid for wheat consumption within the limits of 1 million tonnes (at least). The results of the DD scenarios are given in Appendix 9.

4.7.2 Demand Driven Technological Development

In the Technological Development (TD) scenarios, the link between land productivity and land price described in Section 4.1.7 is switched on. This has a dramatic influence on the results. The domestic wheat production in the scenario countries increases due to increased demand driven intensification. Furthermore, intensification compensates almost fully for displacement of non-wheat crops. This means that the expansion of the agricultural area is reduced by a quarter in the Brazilian scenario, by more than half in the US scenario, and by roughly 80% in the Chinese and Danish scenarios. The results of the TD scenarios are given in Appendix 10.

4.7.3 Armington Elasticities

As discussed in Appendix 1, the Armington elasticities tend to increase with the time perspective. The effects of increasing the Armington elasticities are therefore investigated. Elasticities twice as high as those in the core scenarios are applied in the double Armington (DA) scenarios and yet another doubling of the core scenario elasticities is applied in the quadruple Armington (QA) scenarios. The results show that the higher the Armington elasticities are; the more wheat is imported in the scenario countries. This is because the home product bias is reduced and the foreign products are considered more equal to the domestic crops. Furthermore, the inertia of the trade flows is reduced to simulate more time for signing new contracts, etc. The land use consequences depend on the production patterns of the foreign crop suppliers. In the Brazilian scenario, increased Armington elasticities result in a decrease in the global expansion because Brazil's own fraction of the increased global crop production (with a large contribution from expansion) goes down. In the Danish and Chinese scenarios, expansion goes up due to the change in crop suppliers (compared to the core scenarios) and, in the US scenario, the global expansion decreases slightly when the Armington elasticities are increased. The results of the DA and QA scenarios are given in Appendix 11 and 12, respectively.

4.7.4 Alternative Cropland Area

Cropland on cultivable land (overlay data) is representing the total cropland area ($A_{crop,r}$) in the GTAP Model (see Fig. 7). This is in agreement with the definitions of the two land types, cultivable and grazable land, which state that crops can grow on cultivable land but not on grazable land. However, the actual cropland area estimated by Ramankutty et al. (2007) is somewhat larger (~13% at the global level) than the area of cropland on cultivable land (see Appendix 5, Section 18.1.9 and 18.3.1). The influence of using the 'cropland area in 2000' estimated by Ramankutty et al. (2007) to represent the total area of cultivable land in the crop sectors ($A_{crop,r}$) is therefore investigated in this sensitivity analysis. The rationale is that, although the total cropland area is not fully constituted by cultivable land, the area of grazable land grown with crops has *been made* cultivable (by use of irrigation or other aids).

Modelling the increased wheat demand with a different land use area does not change the total increase in production in the wheat sectors (compared to the core scenarios). However, it does slightly affect the distribution of the production from change in area in the scenario countries. The reason is that this distribution is depending on the wheat yield, which in turn depends on the cropland areas (see formulas in Fig. 8).

The total increase in production in the non-wheat crop sectors also remains the same. However, with an increased cropland area and unchanged production, the initial crop yields are reduced (see Appendix 6f, table 13). The decrease in wheat yields means that a larger increase in the wheat area is necessary to obtain the increase in production. This means that a larger area with other crops is suppressed (increased displacement). This could have been cancelled out by the generally lower crop yields but it is not. This is because the wheat yields are among the lower yields in the 8 crop sectors (see Appendix 6, table 13). The area related reduction of non-wheat crop production is therefore larger in the scenarios with a larger cropland area. Meanwhile, the compensation in terms of intensification is also larger, which means that the total change in production in the crop sectors remains the same compared to the core scenarios.

The expansion increases with the alternative cropland area. To begin with, the GTAP output describing the change in use of cultivable land is affected. The reason is that the relative distribution of land in the GTAP Database (illustrated in Fig. 7) changes. This distribution affects the scaling factor converting the change in production capacity to physical land area (see Section 4.1.4). Secondly, the GTAP output expressing the change in cultivable land use is now multiplied with a larger area in the conversion of the results (see last part of Section 4.4). This means that the total expansion on cultivable land increases by 3% in the Brazilian scenario and by 7-9% in the three other scenarios. The expansion on grazable land turns out to be unaffected by the change in cropland area. The total increase in expansion is 3-7% larger than in the core scenarios. The results of using the alternative estimation of the cropland area ($A_{crop,r}$) in the modelling are shown in Appendix 13.

Fig. 15 compares the reciprocal wheat yields with the global expansion induced by wheat consumption in the scenarios simulated with the alternative cropland area.

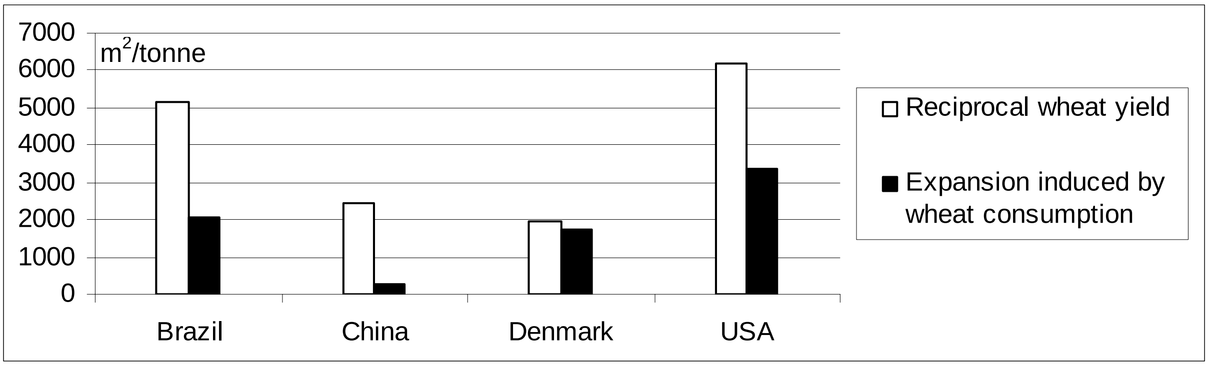


Fig. 15: Comparison of reciprocal wheat yields and expansion results with the alternative cropland area

4.8 Uncertainties in the Economic Modelling

The estimation of cultivable and grazable land available for agriculture is based on a general procedure assuming equal overlap between steep areas, protected areas, and deserts as well as equal distribution of steep and protected areas on cultivable and grazable land (see Appendix 5, Section 18.1.4). This general procedure inevitably results in some errors in the estimation of land type availability and thereby results in over- or underestimation of land type utilisation. This creates inherent uncertainties in the use of the land supply curves. It has not been possible to assess the discrepancies with the data available in the present PhD project.

The area of grazable land available for agriculture may be somewhat overestimated as it includes drylands such as arid, semi arid, and dry sub-humid areas. This is based on the assumption that even natural areas with low fertility will contain some vegetation that can support livestock production. The problem is that grazable land constitutes one land type and there is no distinction between different qualities. Furthermore, the utilisation of grazable land (in the land supply curves) may be slightly underestimated (see Appendix 5, Section 18.1.8). This aspect also influences the results for expansion on grazable land in an upward direction. However, the error introduced by the overestimation of the grazable land area and the underestimation of grazable land utilisation is assumed to be rather low as grazable land only constitutes a minor part of the total expansion (see Fig. 13).

The distribution of cropland among crop sectors is based on the distribution of area harvested in each sector (see Fig. 7). As the (yearly) area harvested is not necessarily equal to the total cropland area (which may include temporary fallow), this procedure also introduces some uncertainty. Although this may cause errors in the estimation of area changes in the single crop sectors, it is only assumed to have a minor influence on the total expansion because underestimation of area change in one sector will tend to be cancelled out by overestimation in another sector.

5 Natural Potential Vegetation Affected by Agricultural Expansion

Knowing the location and magnitude of the land use changes induced by crop consumption is the first premise for performing a life cycle impact assessment of these land use changes. It is, however, also necessary to know the characteristics of the areas affected in order to determine the environmental impacts. A method is therefore developed to characterise the areas affected by agricultural expansion in terms of their *natural potential vegetation* also designated the *biome* (Ramankutty and Foley 1999). This procedure is described in detail in Article 3 (Kløverpris 2008) and summarised here.

The method takes its point of departure in the eight regions representing more than 90 percent of the global expansion estimated in the four core scenarios described in Section 4.5 and 4.6. This means that the method development has evolved around agricultural expansion in the eight regions listed in Table 3.

Table 3: The eight regions representing more than 90% of global agricultural expansion caused by wheat consumption in respectively Brazil, China, Denmark, and the USA

Code	Multi country regions	Code	Single country regions
xeu15	EU15 excl. Denmark	aus	Australia
xsu	Former Soviet Union excl. the Baltic States	bra	Brazil
xla	South America excl. Brazil and Peru	can	Canada
xss	Sub-Saharan Africa excl. SACU*	usa	USA

* Southern African Customs Union: Botswana, Lesotho, Namibia, South Africa, and Swaziland.

5.1 Assessment of Land Type Utilisation Trends

As mentioned in Section 3.4, a distinction is made between two types of expansion, namely accelerated transformation (in areas with an increasing agricultural area) and delayed relaxation (in areas with a decreasing agricultural area). In order to determine the type of expansion taking place on the two land types (cultivable and grazable land), it is therefore necessary to determine the trend in their utilisation. If the trend in the utilisation of cultivable land is falling, the type of expansion will be delayed relaxation. This also means that, within the region, the expansion will be expected to take place in areas where the utilisation of this land type is falling. In other words, the trend in land utilisation not only determines the type of expansion but also the location(s) within a region.

As the map of agricultural land use (cropland and pastures) developed by Ramankutty et al. (2007) is only available for the time around the year 2000, it is not possible to determine the trend in land type utilisation based on this data alone. It is therefore supplemented with data on the development in agricultural land use from FAOSTAT (2007) and the following assumptions:

<u>Assumption 1</u>: If the cropland area in a region is increasing, the utilisation trend for cultivable land is positive.

Assumption 2: If a region's cropland and pasture areas are both increasing, the utilisation trend for both cultivable and grazable land is positive.

Assumption 3: If a region's cropland and pasture areas are both decreasing, the utilisation trend of both cultivable and grazable land is negative.

The rationale behind the assumptions has been discussed in Article 3 (Kløverpris 2008). Some extra considerations to the second assumption are presented in Appendix 14. Because the method development has evolved specifically around the eight regions listed in Table 3, there may be certain types of regions for which the list of assumptions would have to be expanded.

After assessing the utilisation trends for cultivable and grazable land, the areas affected by expansion within the relevant region are located. The procedure depends on whether it is a multi country region or a single country region (see Table 3).

5.2 Locating Expansion on Cultivable Land in Multi Country Regions

If the utilisation trend for cultivable land in a multi country region is positive, the individual countries with an increasing cropland area (based on the latest 10 year period available in FAOSTAT 2007) are identified. It is assumed that expansion on cultivable land predicted by the modified GTAP Model in the relevant region will take place in the identified countries as accelerated transformation. Similarly, expansion in multi country regions with a negative utilisation trend for cultivable land is assumed to take place as delayed relaxation in countries with a decreasing cropland area. If a multi country region contains countries that are very large, the procedure described in the next section is used to locate possible expansion within these countries.

5.3 Locating Expansion on Cultivable Land in Single Country Regions

To determine where expansion in single country regions takes place, cropland maps from 1970 and 1990 are compared. These maps are documented by Ramankutty and Foley (1999) and excerpts are shown in Appendix 15-18. Areas with changes in cropland between 1970 and 1990 are assumed to be the areas affected by expansion on cultivable land. The areas with changes are located by visual inspection of the two maps facilitated by a GIS software tool. Alternatively, a quantitative comparison of the two cropland maps could be performed. However, time and skills did not allow for such an analysis.

5.4 Identifying Biomes Affected by Expansion on Cultivable Land

After locating the areas affected by cultivable land in the relevant regions, the same areas are identified on a global map with 15 different biomes (Ramankutty and Foley 1999). The biomes affected by expansion on cultivable land are thereby identified. The global biome map is shown in Appendix 19. Data on cropland by region and biome (Ramankutty et al. 2007) is used to cross-check the conclusions. This data is presented in Fig. 16. Note that the 15 biomes from the biome map (Appendix 19) have been aggregated to four main biomes in Fig. 16.

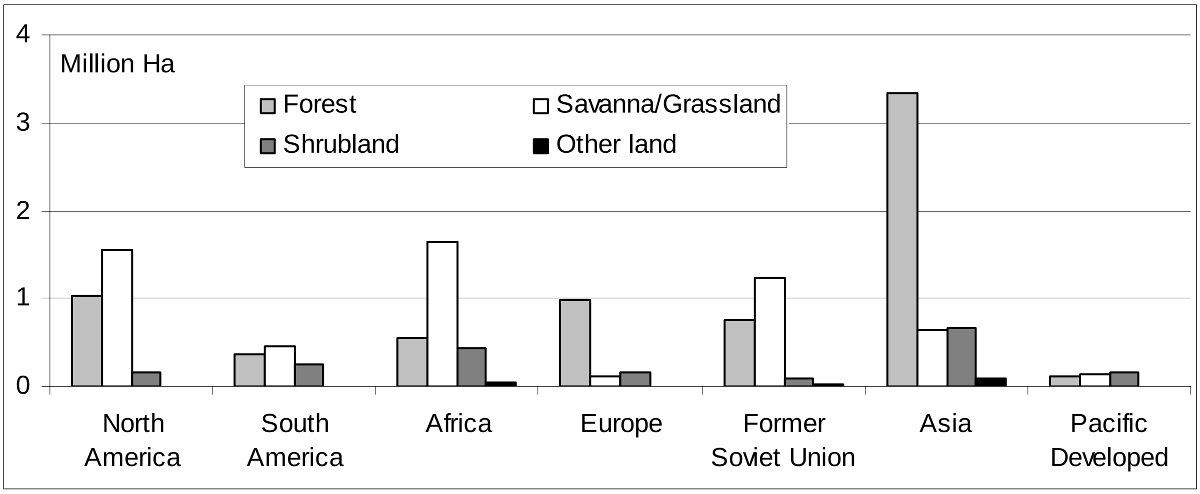


Fig. 16: Cropland by region and main biomes (Ramankutty et al. 2007)

5.5 Locating Expansion on Grazable Land in Multi Country Regions

If the utilisation trend for grazable land in a multi country region is positive, the individual countries with an increasing pasture area (based on the latest 10 year period available in FAOSTAT 2007) are identified. These countries constitute the candidates for areas affected by the expansion predicted by the modified GTAP Model on grazable land in single country regions. Similarly, countries with a decreasing pasture area constitute the candidates for areas affected by expansion in multi country regions with a negative utilisation trend for grazable land. If a multi country region contains countries that are very large, the procedure described in the next section is used to locate possible expansion within these countries.

5.6 Locating Expansion on Grazable Land in Single Country Regions

To locate the areas affected by expansion on grazable land in single country regions, two global maps with agricultural land use are used to identify the frontiers between pastures and nature. One map shows pastures only and the other map shows both pastures and cropland (Ramankutty et al. 2007). These areas located on the identified frontier between pastures and nature constitute the candidates for areas affected by expansion on grazable land in single country regions.

5.7 Identifying Biomes Affected by Expansion on Grazable Land

The areas selected as candidates for areas affected by expansion on grazable land are located on the global biome map. If they appear to be located on biomes already characterised as cultivable land, they are discarded[15]. Otherwise, the biomes in these areas are assumed to be those affected by expansion on cultivable land in the relevant region. Data on pastures by regions and main biomes (Ramankutty et al. 2007) is used to support the conclusions. This data is presented in Fig. 17.

[15] The frontier between pastures and nature may be found on cultivable land.

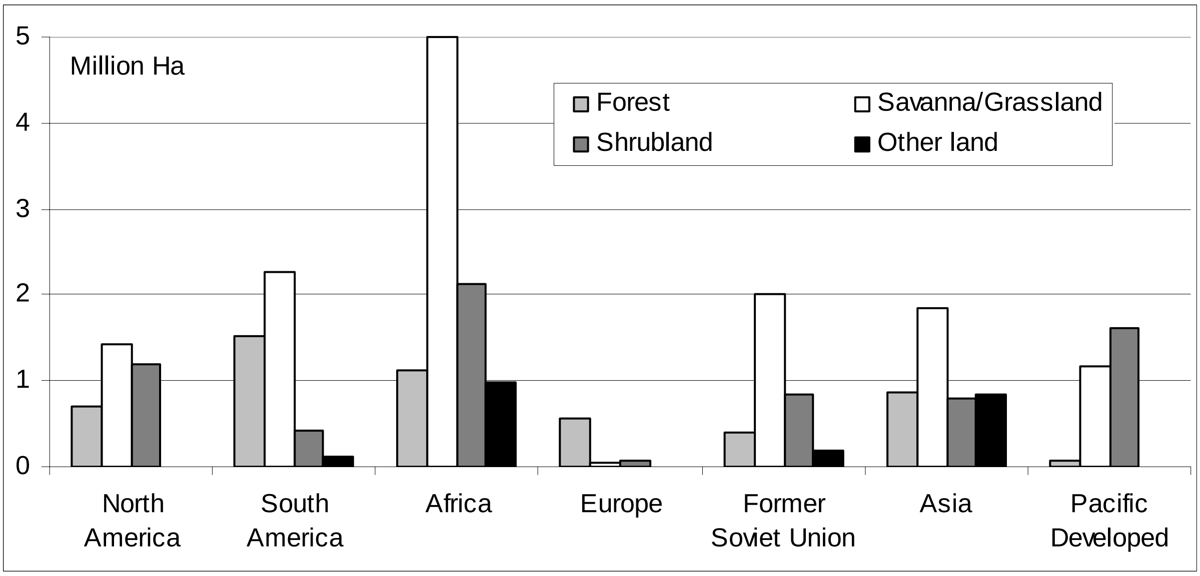


Fig. 17: Pastures by region and main biomes (Ramankutty et al. 2007)

5.8 Results: Biomes Affected by Regional Agricultural Expansion

In Article 3 (Kløverpris 2008), it is demonstrated how the method summarised above is applied in practise to the eight regions in Table 3. The results are listed in Table 4.

Table 4: Biomes affected by agricultural expansion. If two biomes are mentioned for the same region, expansion is expected to affect equal shares. Expansion type is given in brackets. AT stands for accelerated transformation and DR stands for delayed relaxation.

Region	Biomes affected on cultivable land	Biomes affected on grazable land
aus	Savanna (AT)	Open shrubland + grassland/steppe (DR)
bra	Tropical evergreen forest (AT)	Savanna (AT)
can	Boreal deciduous forest (DR)	Boreal evergreen forest (DR)
xeu15	Evergr/dec. mix. forest + dense shrubland (DR)	Dense shrubland (DR)
xsu	Grassland/steppe (DR)	Evergreen/deciduous mixed forest (DR)
xla	Grassland/steppe + trop. evergreen forest (AT)	Savanna + dense shrubland (DR)
xss	Tropical evergreen forest + savanna (AT)	Open shrubland (AT)
usa	(Full utilisation of cultivable land)	Open shrubland (DR)

5.9 Uncertainties in the Identification of Biomes Affected by Expansion

Although the biome analysis presented above is partly based on qualitative data, the qualitative nature of the assessments causes some uncertainties concerning both the land type utilisation trends and the biomes pointed out as those being affected by agricultural expansion. In Article 2 (Kløverpris 2008), these uncertainties are discussed and characterised region by region. This characterisation is presented in Table 5.

Table 5: Certainty of the results for the eight regions studied. 'Very good' means that the result is considered unambiguous, 'good' indicates a high degree of certainty, and 'moderate' indicates some uncertainty about a result. The certainty is not considered 'poor' (or very uncertain) for any of the results.

Region	Land type utilisation trends	Biomes affected by expansion
aus	Very good	Moderate
bra	Very good	Good
can	Moderate	Moderate
xeu15	Good	Moderate
xsu	Good/moderate	Moderate
xla	Moderate	Moderate
xss	Very good	Moderate/good
usa	Good	Moderate

6 Land Use Life Cycle Inventory for Wheat Consumption

Based on the results from the economic modelling and the assessment of biomes affected by expansion on cultivable and grazable land (Table 4), a land use LCI is produced for the consumption of one tonne of wheat in respectively Brazil, China, Denmark, and the USA (see Table 6). The land use LCI quantifies the biomes affected by agricultural expansion and subsequent agricultural occupation for a period of one year.

Table 6: Land use LCI for consumption of one tonne of wheat in Brazil, China, Denmark, and the USA (core scenarios). Numbers indicate the areas of biomes affected by agricultural expansion (accelerated transformation or delayed relaxation) followed by one year of agricultural occupation. Inconsistencies occur due to rounding.

	Brazilian core scen.	Chinese core scen.	Danish core scenario	US core scenario
Savanna	230 m^2	53 m^2	300 m^2	590 m^2
Tropical evergreen forest	1,500 m^2	44 m^2	350 m^2	460 m^2
Boreal deciduous forest	57 m^2	49 m^2	97 m^2	850 m^2
Evergreen/deciduous mixed forest	25 m^2	14 m^2	200 m^2	160 m^2
Dense shrubland	29 m^2	10 m^2	260 m^2	140 m^2
Grassland/steppe	120 m^2	24 m^2	150 m^2	210 m^2
Open shrubland	43 m^2	38 m^2	170 m^2	480 m^2
Boreal evergreen forest	4 m^2	4 m^2	10 m^2	51 m^2
Rest (biomes unknown)	35 m^2	24 m^2	130 m^2	210 m^2
Total net expansion	2,000 m^2	260 m^2	1,700 m^2	3,200 m^2

In Table 6, no distinction is made between the two types of expansion (accelerated transformation and delayed relaxation). The reason is that the two types of expansion may be assumed to have the same impact (see Article 2: Kløverpris et al. 2008b). It is, however, also possible to distinguish between the two types of expansion. This is demonstrated for the Brazilian core scenario in Table 7, which also distinguishes between expansion on respectively cultivable and grazable land.

Table 7: Land use LCI for consumption of one tonne of wheat in Brazil (core scenario). Numbers indicate the areas of biomes affected by agricultural expansion followed by one year of agricultural occupation. Inconsistencies occur due to rounding.

Expansion type	Accelerated transformation		Delayed release	
Land type	Cultivable	Grazable	Cultivable	Grazable
Savanna	65 m^2	160 m^2	0 m^2	0 m^2
Tropical evergreen forest	1,500 m^2	0 m^2	0 m^2	0 m^2
Boreal deciduous forest	57 m^2	0 m^2	0 m^2	0 m^2
Evergreen/deciduous mixed forest	0 m^2	0 m^2	8 m^2	17 m^2
Dense shrubland	0 m^2	10 m^2	8 m^2	11 m^2
Grassland/steppe	94 m^2	0 m^2	17 m^2	5 m^2
Open shrubland	0 m^2	39 m^2	0 m^2	5 m^2
Boreal evergreen forest	0 m^2	0 m^2	0 m^2	4 m^2
Rest (biomes unknown)	30 m^2	5 m^2	0 m^2	0 m^2
Total	1,700 m^2	220 m^2	33 m^2	42 m^2

The increased crop production induced by increased wheat consumption leads to displacement of pastures on cultivable land or, in other words, conversion of cultivable land from pastures to cropland. This is partly compensated for by converting unused grazable land (nature) to pastures, which is also accounted for in the results (included in the black part of the bars in Fig. 13). However, the environmental impacts caused by converting pastures to cropland (or the opposite) cannot be assessed based on the results presented in Table 6 and Table 7. It is, however, possible to list all conversion between cropland and pastures based on the data in Appendix 6. These results are not presented in this PhD dissertation as focus is on expansion of the agricultural area and not conversion of the existing agricultural area. It should also be noted that, in order to estimate the environmental consequences of conversion between cropland and pastures, it would be necessary to assess the ongoing trend in this conversion to consider if increased crop consumption accelerates or delays conversion (analogously to the assessment of the trends in land type utilisation).

7 Discussion

As the main focus of the present PhD dissertation is the land use changes, the intensification aspect has only received some attention. Intensification is therefore discussed in more detail below. Furthermore, some theoretical offshoots of the PhD project with more general relevance for LCA are discussed. For further discussion of the methods and results described in the previous chapters, the reader is referred to the article collection in Chapter 13.

7.1 Environmental Consequences of Intensification

Expansion and intensification are two sides of the same coin called marginal crop production, i.e. the crop production caused by a change in crop demand. The marginal crop production not obtained by expansion is achieved via intensification and vice versa. The PhD project presented in this dissertation focuses mainly on the expansion side and the preparation for LCIA. However, the project also goes a long way in the preparation for LCIA on the intensification side. First of all, it is determined how much of marginal crop production that is achieved by respectively expansion and intensification[16]. This information provides the basis for elaborating an LCI for intensification.

If increased crop demand is assumed not to result in further technological development, the intensification of production is merely achieved by optimising inputs (fertilisers, pesticides, and water) to price changes (see Section 3.5). The first step in the elaboration of an LCI for intensification is to determine how much the inputs to the field are increased. There are several ways to approach this problem. One is discussed in Article 1 (Kløverpris et al. 2008a) where it is proposed to multiply the changes in intermediate inputs to the different crop sectors (GTAP output) with the known inputs to crop production. For example, the relative change in intermediate inputs to the wheat sector in the USA could be multiplied with the amount of fertilisers and other inputs applied in this sector. The current levels of inputs to the agricultural sectors in the different regions could be obtained from national agricultural statistics or estimated based on the monetary values given in the GTAP Database. If input data cannot be established for each crop sector in each of the relevant regions, a simpler approach would be to estimate the aggregate change in inputs to the crop sectors in each region. This would also provide a basis for determining the total increase in the use of fertilisers and other inputs. Finally, another approach could be to determine the change in inputs based on the yield increases in the different crop sectors given in Appendix 6. The work of Schmidt (2007) may serve as an inspiration for this approach. Once the changes in inputs to crop production are determined, the next step is to determine the resulting emissions. This issue is not discussed in the present dissertation.

[16] As mentioned in Chapter 2, this was one of the questions rendered unanswered by Schmidt (2007).

7.2 Budget Constraints in LCA

Using a general economic equilibrium model to estimate the land use consequences of increased crop consumption requires that the budget constraint of the consumer is acknowledged (see Section 4.3). This is an aspect not commonly considered in LCA although at least one study has taken it into account: Thiesen et al. (2006) studied the environmental impacts entailed by the consumption of two types of cheese. One is more expensive than the other and thereby absorbs more of the consumer's budget. If this is not taken into account, the cheaper cheese comes out as the environmentally preferable choice for nutrient enrichment and acidification, but not for photochemical ozone formation and global warming. Meanwhile, the cheaper cheese leaves more money for consumption of other goods than the expensive cheese. Thiesen et al. (2006) therefore estimated the marginal consumer expenditure, i.e. the goods bought by the consumer for the last or extra available money in the budget. When this aspect is taken into account, the expensive cheese comes out as the most environmentally friendly choice in all impact categories. This shows the significance of budget constraints in environmental assessment.

Thiesen et al. (2006) mention that their study does not consider the spending of the profit earned from the sale of the cheese and, ideally, they would like these consequences to be investigated further. However, it seems fair to omit this aspect as the price of a product in a free market can normally be assumed to constitute the marginal production costs (Weidema 2003), i.e. the possible differences in profits can be ignored. Nevertheless, as also stated by Thiesen et al. (2006), the choice of cheese may have some economic distributional consequences, which are not considered in the study. Such distributional consequences can, to some extent, be captured by a general equilibrium model because it includes the entire economy. Meanwhile, the sectors in economic models often represent several products and it may be difficult to distinguish between similar goods. At least, it is not likely to find an economic model that distinguishes between cheap and expensive cheese.

Although the budget constraint of the households is taken into account in the present PhD project, the marginal consumer expenditure is only poorly determined. In fact, the marginal consumer expenditure is modelled as the *average* consumer expenditure because the increase in wheat consumption is assumed to equally affect all other goods bought by the households (see Section 4.3). The results of the PhD project may therefore be improved by simulating increased wheat demand at the expense of marginal (and not average) consumer expenditure.

Finally, it is important to keep in mind that the shocks to wheat demand are placed in the households to create a change in demand, which is as neutral as possible and thereby as generally applicable as possible. Placing the shock elsewhere in the economy would have had other distributional effects and thereby other land use consequences (see Baltzer and Kløverpris 2008).

7.3 LCI Data Modelled with General Equilibrium Models

As shown in Section 4.5, the increased wheat production modelled in this PhD project is accompanied by a decrease in the production of other crops. There are two main reasons for this. The first one is that all sectors in the economy compete for production factors (see Appendix 1). Even if raw materials are available in plenty supply, increased production requires labour and/or capital. This means that increased wheat demand will move production factors to the wheat sector. This leads to reduced production in the other sectors, including the non-wheat crop sectors. The other reason for the reduced production of non-wheat crops has to do with the budget constraint (see previous section). As already discussed, the increase in wheat demand is constructed at the expense of the demand for other products. This means that the reduced production of non-wheat crops is partly explained by reduced demand. The influence of the decrease in demand compared to the competition for productions factors is not determined. However, the competition for the production factor land is assumed to be one of the main reasons for the decrease in non-wheat crop production.

More generally, construction of LCI data in a general equilibrium model requires that the budget constraints are respected, i.e. an increase in demand for one product must be modelled at the expense of other products. Although this is unusual in the construction of LCI data, it reflects an actual premise of the economy. In fact, it is not so different from life cycle assessment, which is typically used for comparison of alternatives or, in other words, comparison of an increased demand for one solution and a reduced demand for another. If LCI data is modelled consistently in a general equilibrium model at the expense of the same product groups (marginal expenditure), the influence of these products will tend to cancel out once the LCI data is combined in a full LCA. However, there will typically be a price difference between the alternatives being compared (as for the two types of cheese described in the previous section). This means that not all of the marginal expenditure will cancel out. The residual marginal expenditure that does not cancel out will correspond to the price difference between the two alternatives. This is illustrated with an example (see Fig. 18): Consider a shift from a chemical to an enzymatic production technology. This implies an induced flow of enzyme. Assume that the enzyme in turn avoids the use of chemical and reduces the need for energy. Furthermore, assume that the enzymatic solution is cheaper than the chemical solution and that all LCI data is modelled in a general equilibrium model at the expense of the same marginal expenditure. The LCI data for the enzyme would then reflect an avoided marginal expenditure corresponding to the price of the enzyme. Likewise, the LCI data for the avoided chemical and energy production would reflect induced marginal expenditure. The marginal expenditure reflected by the enzyme data would then be cancelled out by the marginal expenditure reflected by the chemical and energy data. Meanwhile, some of the marginal expenditure related to the chemical and energy would not cancel out. This is exactly the part corresponding to the savings obtained from shifting to the enzymatic technology. This shows how the suggested proposal for LCI data can inherently account for the rebound effects discussed by Thiesen et al. (2006).

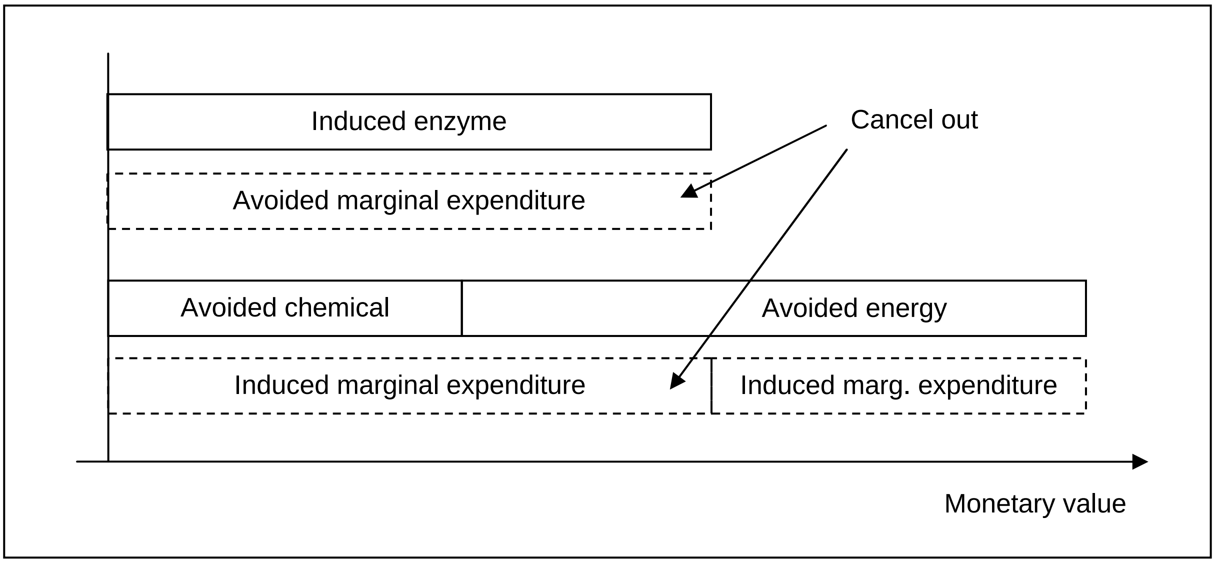


Fig. 18: Fictitious illustration of how LCI data reflecting the marginal expenditure suppressed by the choice of a commodity can inherently account for the environmental implications of price differences between two alternatives being compared (in this case an enzymatic and a chemical process).

The marginal expenditure is most relevant for life cycle assessment of consumer products. The reason is that price savings in industry are likely to be internalised, e.g. invested in more production capacity. Reduced production costs will also make the relevant sector more competitive, which will have distributional consequences which are not easy to predict. Nevertheless, the approach described (modelling LCI data in a general equilibrium model and thereby inherently accounting for marginal expenditure) could be seen as a new way forward in LCA, which is more in line with the actual mechanisms of the economy. Note that this discussion is mainly of general relevance for LCA. It is only considered to have a minor influence on the land use results presented in this dissertation.

8 Conference on Sustainability Assessment of Biofuels

Many aspects of the PhD project presented in this dissertation are of relevance for the environmental assessment of biofuels and, as part of the PhD project, an international workshop and conference on the sustainability assessment of biofuels was organised. The full title of the conference was *Modelling Global Land Use and Social Implications in the Sustainability Assessment of Biofuels*. The conference was officially organised by the Technical University of Denmark, University of Southern Denmark, Danish Institute for Product Development, and OECD. It was co-sponsored by Novozymes A/S and Unilever and also supported economically by the Danish Research Council for Technology and Production Sciences. The conference took place in Copenhagen on 4-5 June 2007. Approximately 40 international scientists from the fields of environmental assessment, economic modelling, geography, and sociology took part in the event. Roughly one-quarter of these people focused on the social implications of biofuels and the remaining three-quarters focused on the land use issue. The first day of the conference consisted of an open plenary session with presentations from invited speakers including a presentation of preliminary results from Article 2 (Kløverpris et al. 2008b). The second day took place as a workshop with 4 working groups. A draft version of Article 1 (Kløverpris et al. 2008a) was distributed among the participants prior to the conference to inspire the debate.

Results presented at the conference supported the conclusion that land use changes caused by changes in crop consumption depend on the geographical location of the studied consumption and that several crop suppliers around the world will be affected by a change in crop demand. Furthermore, the participants generally agreed that some regions of the world hold large potentials for intensification because they are currently not using the resources optimally due to a number of barriers, e.g. low access to capital, knowledge, fertilisers, and markets. The effects of legislative fertiliser constraints were also acknowledged (see Section 3.5.1) and it was generally agreed that the modelling of land use changes caused by increased biofuels production requires an interdisciplinary approach incorporating economic modelling and geographical data as a minimum but possibly also agronomy and soil science. Kløverpris et al. (2008c) (Appendix 20) summarise the main results and discussions from the conference and synthesise the findings relevant for life cycle inventory modelling of land use caused by the increased biofuels demand.

9 Conclusions

This chapter summarises the main conclusions from the PhD project presented in the present dissertation.

9.1 Conceptual Analysis

The conceptual analysis of crop production shows that several issues play an important role in the identification of land use changes caused by increased crop demand. The supply elasticity of crops influences the amount of crops produced in response to an increased demand and thereby has an influence on the land use changes. So does the methods applied when production of a given crop is increased. Displacement of other crops and/or livestock leads to (partial) replacement of this production elsewhere. The displacement-replacement mechanisms channel the response to increased crop demand through the global agricultural system. Ultimately, increased crop production can only be achieved by expansion or intensification.

Expansion caused by a marginal change in crop consumption is seen in relation to the ongoing trend in land utilisation. If land utilisation is increasing, expansion occurs by accelerated transformation of natural land. If land utilisation is falling, expansion occurs by delayed relaxation of land being released to nature.

Increased crop production achieved by intensification is divided into two categories. The first is called optimisation of production and concerns the adjustment of agricultural inputs to the field (fertilisers, pesticides, and irrigation) with the purpose of maximising profits. This is governed by input and crop prices as well as the relationship between inputs and crop yields. This relationship is characterised by diminishing returns, i.e. the more inputs applied, the lower is the additional yield achieved per unit of input. Intensification can also be achieved through technological development within mechanical aids, crop strains, and agricultural practices. This development is partly driven by internal competition between suppliers of respectively mechanical aids and crop strains but also internal competition among the farmers. Improvement of agricultural practises is mainly controlled by national institutions and thus driven by political decisions. Furthermore, technological development is to some extent influenced by changes in the demand for crops but it is difficult to quantify this relationship.

Finally, the geographical location of changes in crop consumption and thereby crop demand influences the land use consequences because trade costs such as transport and tariff costs influence the prices of crops and thereby the ratio between intensification and expansion.

9.2 Method Characteristics

Many of the mechanisms influencing the land use change caused by increased crop consumption can be simulated with the economic general equilibrium model called GTAP (Global Trade Analysis Project). The model determines the supply elasticity of crops and is able to handle both the displacement-replacement mechanisms and the implications of trade costs. By introducing two new land types and corresponding regional land supply curves based on global geographical datasets, the model is enabled to predict the global expansion of the agricultural area caused by increased crop consumption. This also allows for a realistic estimation of the ratio between intensification and expansion. However, the model does not account for diminishing returns in crop production or legal restrictions on the use of agricultural inputs. Furthermore, the simulation of increased wheat demand must be performed at the expense of the demand for other goods.

The natural potential vegetation (the biome) of the areas affected by agricultural expansion can be assessed by use of agricultural statistics and maps of global agricultural land use and the global biome distribution. First, the trend in land utilisation is determined and, on this basis, the expansion type (accelerated transformation or delayed relaxation) is determined and it is assessed which biomes that are affected.

9.3 Method Demonstration

Consumption of one extra tonne of wheat in respectively Brazil, China, Denmark, and the USA is estimated to result in a global increase in wheat production between 880 kg (Brazil) and 1100 kg (China). The net increase in wheat production (excluding the wheat used for seeds) is between 840 kg (Brazil) and 980 kg (China). Brazil and China cover most of the increase in wheat consumption by domestic production (84% and 97%, respectively) while Denmark and the USA obtain a large share from changes in trade flows (roughly half and two-thirds, respectively).

Intensification accounts for almost 30% of the increase in global wheat production caused by increased wheat consumption in Denmark. This may be overestimated because restrictions on fertilisers are not accounted for. Intensification accounts for approximately 20% of the global increase in wheat production caused by wheat consumption in Brazil, China, and the USA.

Roughly 40% of the Brazilian increase in wheat production comes from displacement of other crops and livestock, and another 40% comes from expansion. In China, Denmark, and the USA, increased wheat production is only achieved by displacement and intensification. In Brazil and China, the displacement of non-wheat crops is almost fully compensated for by intensification (92% and 78%, respectively). In Denmark and the USA, displacement of non-wheat crops is partly compensated for by intensification but mainly by changes in trade flows.

The displacement of livestock on cultivable land (conversion of pastures to cropland) is partly compensated for by moving livestock production to grazable land (conversion of nature to pastures). Furthermore, the displacement is also partly compensated for by substitution with capital and labour. Consequently, the displacement of livestock only has a minor influence on livestock production.

Global agricultural expansion caused by increased wheat consumption varies considerably depending on where the consumption takes place. One extra tonne of wheat consumed in China is estimated to result in a global expansion of 260 m^2 whereas the same consumption in the USA results in an estimated expansion of roughly 3200 m^2. The biomes assessed to be affected by wheat consumption in China and the USA are mainly savanna, boreal deciduous forest, open shrubland, and tropical evergreen forest. The global expansion caused by the consumption of one extra tonne of wheat in Brazil is approximately 2000 m^2 and mainly presumed to affect tropical evergreen forest in the country itself. In Denmark, increased wheat consumption of one tonne leads to an estimated global expansion of roughly 1700 m^2. This is mainly presumed to affect savanna, tropical evergreen forest, and dense shrubland.

The results are valid for changes in wheat consumption up to 1 million tonnes per year but larger changes can also be studied with the presented method. Demand driven technological development can be included in the modelling but, without any knowledge on the exact relationship between demand and technological development, the results only serve as an illustration. The results are sensitive to changes in the Armington elasticities that express perceived and actual heterogeneity between domestic and foreign products as well as the inertia of global trade patterns.

10 Recommendations for Future Work

The PhD project described in this dissertation is mainly a demonstration project. It identifies aspects of importance for the modelling of land use LCI data for crops and illustrates how most of these issues can be handled by use of economic modelling, agricultural statistics, and geographical land use and land cover data. However, the project leaves room for further improvement.

10.1 Land Supply Curves

The assessment of the availability of cultivable and grazable land (A_a) could be improved. The general procedure and the assumptions concerning the distribution of protected and steep areas as well as the overlaps between these areas and deserts need further revision. Optimally, these issues should be assessed country by country. As this is a comprehensive task, the most important countries could be considered to begin with. As mentioned in Section 4.8, the estimation of land that can be used as pastures may be overestimated so this assessment should be refined. Furthermore, crops occupying grazable land should be counted in the calculation of the utilisation level for this land type (see Appendix 5, Section 18.1.9).

10.2 Restrictions on Agricultural Inputs

Legal regulations concerning the use of fertilisers, pesticides, and irrigation should be included in the modelling of land use LCI data for crops (see Section 4.2).

10.3 New FAOSTAT Data

During the elaboration of the present PhD project, the FAOSTAT database went through a major revision (which meant that some data was not accessible for a longer period of time). However, now that the new version is more or less complete, new land use data has become available including detailed data on irrigation of agricultural areas. This might provide new possibilities for integrating this aspect in future modelling. It is recommended that this option is explored.

10.4 Alternative Shocks to Crop Demand

As described in Section 4.5, the existing trade patterns have a significant influence on the results. This means that the wheat suppliers affected by a change in household wheat demand are mainly those already selling wheat to the households in the scenario country. It is therefore recommended to investigate the consequences of changes in wheat demand elsewhere in the economy. The challenge is to construct a shock to the wheat demand, which does not create too many secondary effects that will influence the land use change. Secondary effects could be changes in the competitiveness of a sector in which the wheat demand is changed. To be more concrete, this can be illustrated by an example. During the PhD project, experiments were made with shocks to the wheat demand in the food processing sector[17]. The approach described in Section 4.3 was used, i.e. the sector's demand for wheat was increased

[17] Results for the US scenario are available in Baltzer and Kløverpris (2008)

by 500,000 tonnes at the expense of the demand for other commodities bought by the sector. Again, the decrease in the demand for other commodities was distributed equally (same percentage change). It was therefore a different product mix that was affected compared to the household shocks. Because the food processing sector uses a large amount of crops, the decrease in demand affected non-wheat crops to a much higher degree. This means that the net increase in crop demand[18] was smaller in the food processing shocks compared to the household shocks resulting in a downward influence on the agricultural expansion. This is an example of an unintended secondary effect. Furthermore, the shock to the wheat demand in the food processing sector forced this sector to choose an economically suboptimal input mix because of the changes in buying preferences (more wheat and less of other commodities). This meant that the sector's competitiveness was reduced. This secondary effect also had an indirect influence on the estimated agricultural expansion. This was another reason for discarding the shocks to wheat demand in the food processing sector. Nevertheless, it is recommended to try and model shocks to crop demand outside the households. The key to a meaningful result may be to change the way in which the budget constraint is kept. One option may be to increase the wheat demand at the expense of non-food commodities or, once and for all, determine marginal expenditure (see Section 7.2). The reason why it is interesting to study changes in crop demand outside the households is that the industrial sectors typically buy much more of their inputs on foreign markets. These trade patterns may lead to other expansion results than those observed in the household scenarios. Finally, it is recommended to simulate *decreases* in crop demand to see if this results in production and land use changes similar to those observed in the present study, only with an opposite sign.

10.5 Other Models

It is recommended to try other models than the GTAP Model or other *versions* of the GTAP Model for construction of land use LCI data for crops. Klijn and Vullings (2005) describe a modification of the GTAP Model called LEITAP. This also applies the concept of land supply curves. Furthermore, it is linked with the environmental model IMAGE (Integrated Model to Assess the Global Environment), which is developed to explore the long-term dynamics of global environmental change. Among other things, the IMAGE model is used to adjust the yields calculated in the modelling framework. This takes place in an iterative process where information runs back and forth between the IMAGE Model and the modified GTAP Model. The IMAGE Model works in a spatial grid dimension and is therefore able to account for land heterogeneity. This means that the LEITAP Model framework has some advantages compared to the modified GTAP Model applied in the present study. In fact, the LEITAP team has been contacted but, despite periodic contact, no co-operation on creation of land use LCI data for crops was established. Nevertheless, it would be interesting to use the LEITAP Model for this purpose. Furthermore, the FAO World Food Model, the FAPRI Model, and the Penn State Trade Model (see van Meijl et al. 2006) may be suitable for construction of land use LCI data. These are all partial equilibrium models (as opposed to general equilibrium models), which means that it may be possible to increase the demand for crops without having to reduce the

[18] The increase in wheat demand plus the decrease in the demand for non-wheat crops

demand for other commodities. It may therefore be possible to establish more traditional LCI data with these models (see discussion in Section 7.3).

10.6 Identification of Biomes Affected by Agricultural Expansion

As discussed in Section 5.9 and Article 3 (Kløverpris 2008), the identification of biomes affected by expansion of the agricultural area is subject to some uncertainty. This may be reduced by a disaggregation of the 22 GTAP sectors in the modified version of the GTAP Database. With more and smaller regions, it would be easier to pinpoint areas affected by expansion and assign the right biomes to those. Besides, disaggregated data on the development in agricultural land use in single country regions (see Table 3) could be used for the assessment of land type utilisation trends instead of the visual inspection of maps described in Section 5.4 and 5.6. However, it would be even better to develop a quantitative assessment of biomes affected by expansion based in a GIS setting. Due to lack of adequate skills and time, this approach was not pursued in the present PhD project.

10.7 Land use LCI Database

The ordinary LCA practitioner does not have the possibility to model ultimate land use changes induced by crop consumption in the GTAP Model. In order to move from demonstration to application of the method described in the present dissertation, it is therefore necessary to construct a database with marginal land use LCI data for crops. This should include data for all eight crop sectors in the GTAP Database and for as many regions as possible. Before constructing such a database, it is advised to seek consensus on the Armington issue within the LCA community. Furthermore, the database could be expanded with data on intensification (see Section 7.1) and land use emissions caused by expansion of the agricultural area.

11 Research Stays and Conference Presentations

As part of the PhD project, two visits to universities in the USA were conducted. Furthermore, several presentations were given at conferences and workshops in Europe and the USA. An overview of these activities is presented below.

11.1 Research Stays

Design for Environment Lab
Department of Mechanical Engineering
University of Washington (Seattle), USA
Period: 18 July – 30 October, 2005

Center for Sustainability and the Global Environment (SAGE)
University of Wisconsin-Madison, USA
Period: 31 October – 27 November, 2005

11.2 Conference Presentations

Kløverpris and Baltzer (2007): *Modelling Land Use Changes caused by Increased Crop Demand in Brazil, China, Denmark and the USA*, oral presentation at Biofuel Assessment Conference: Modelling Global Land Use and Social Implications in the Sustainability Assessment of Biofuels, Copenhagen, Denmark, June 2007.

Kløverpris J, Baltzer K, Wenzel H, Nielsen PH (2007): *Consequential Life Cycle Inventory Modelling of Land Use Changes related to Crop Production*, oral presentation at SETAC Europe 17th Annual Meeting, Porto, Portugal, May 2007.

Kløverpris J, Wenzel H, Nielsen PH (2006): *Model for the Identification of Marginal Crop Production in LCA - a pre-requisite for land use impact assessment of crop use*, poster presented at SETAC North America 27th Annual Meeting, November 2006, Montreal, Canada.

Kløverpris (2006): *Inventory Analysis of Crop Production in LCA - a pre-requisite for impact assessment of crop use*, oral presentation at Expert Workshop on Definition of Best Indicators for Biodiversity and Soil Quality for Life Cycle Assessment (LCA), Centre for Environmental Strategy, University of Surrey, UK, June 2006.

Kløverpris J, Wenzel H, Nielsen PH (2006): *Model for the Identification of Marginal Crop Production in LCA - a pre-requisite for land use impact assessment of crop use*, poster presented at SETAC Europe 16th Annual Meeting, May 2006, The Hague, The Netherlands.

12 References

Abler D (2003): Adjustment at the Sectoral Level. In: An IAPRAP Workshop on Policy Reform and Adjustment, The Wye Campus of Imperial College, October 23–25, http://agadjust.aers.psu.edu/Workshop_files/Abler_presentation.pdf

Andersen SB (2006): Written dialogue with Sven Bode Andersen, Professor of plant breeding, Faculty of Life Sciences, Denmark

Andersen JT, Kløverpris J (2004): Environmental Assessment of Enzymatic Biotechnology, IPL-160-04, Department of Manufacturing Engineering and Management, Technical University of Denmark

Baltzer K, Kløverpris J (2008): Improving the land use specification in the GTAP model, Institute of Food and Resource Economics, University of Copenhagen, Working Paper no. 2/2008, available from www.foi.dk

Boserup E (1965): The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure. London, G. Allen and Unwin, 1965; Chicago: Aldine, 1965

Bruinsma J (ed) (2002): World Agriculture: towards 2015/2030: an FAO Perspective. London: Earthscan

Case KE, Fair RC (1999): Principles of Economics (5th edition). Prentice-Hall

Curran MA, Mann M, Norris G (2005): The international workshop on electricity data for life cycle inventories. J Clean Prod 13 (8) 853-862

Dimaranan BV, (ed) (2006): Global Trade, Assistance, and Production: The GTAP 6 Data Base, Center for Global Trade Analysis, Purdue University.

Ekvall T, Weidema B (2004): System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. Int J LCA 9, 161-171

EMFA (2006): Forecast of food, farming and fertilizer use in the European Union 2006-2016, European Fertilizer Manufacturers Association, Avenue E. van Nieuwenhuyse 4, B-1160 Brussels, Belgium

European Commission (2002): Implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Luxembourg: Office for Official Publications of the European Communities

European Commission (2008): Database on environmental taxes, available online at http://ec.europa.eu/environment/enveco/index.htm

European Council (2001): Applying a scheme of generalised tariff preferences for the period from 1 January 2002 to 31 December 2004. Council Regulation (EC) No 2501/2001, Official Journal of the European Communities, L 346/1

FAOSTAT (2007): http://faostat.fao.org, United Nations Food and Agricultural Organisation

FAPRI (2006): U.S. and World Agricultural Outlook. Food and Agricultural Policy Research Institute, Iowa, USA

Hertel TW (1997): Global Trade Analysis: Modeling and Applications. Cambridge University Press

Klijn JA, Vullings LAE (2005): The EURURALIS Study: Technical Document, EURURALIS 1.0 – A Scenario Study on Europe's Rural Areas to Support Policy Discussion. RIVM, Alterra-rapport 1196

Kløverpris J, Wenzel H, Nielsen PH (2008a): Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption. Part 1: Conceptual Analysis and Methodological Proposal. Int J LCA 13 (1) 13-21

Kløverpris J, Baltzer K, Nielsen PH (2008b): Life cycle inventory modelling of land use induced by crop consumption. Part 2: Example of wheat consumption in Brazil, China, Denmark, and the USA, Int J LCA (submitted).

Kløverpris J (2008): Identification of biomes affected by marginal expansion of agricultural land use induced by increased crop consumption, J Clean Prod (submitted)

Lesage P, Ekvall T, Deschênes L, Samson R (2007a): Environmental Assessment of Brownfield Rehabilitation Using Two Different Life Cycle Inventory Models. Part 1: Methodological Approach. Int J LCA 12 (6) 391–398

Lesage P, Ekvall T, Deschênes L, Samson R (2007b): Environmental Assessment of Brownfield Rehabilitation Using Two Different Life Cycle Inventory Models. Part 2: Case Study. Int J LCA 12 (7) 497–513

Mila i Canals L, Bauer C, Depestele J, Dubreuil A, Knuchel RF, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007): Key Elements in a Framework for Land Use Impact Assessment within LCA. Int J LCA 12 (1) 5–15

Nemecek T, Heil A, Huguenin O, Meier S, Erzinger S, Blaser S, Dux. D, Zimmermann A (2007): Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent v2.0 No. 15, Swiss Centre for Life Cycle Inventories, Dübendorf

Nielsen PH, Dalgaard R, Korsbak A, Pettersson D (2008): Environmental Assessment of Digestibility Improvement Factors Applied in Animal Production: Use of Ronozyme® WX CT Xylanase in Danish Pig Production. Int J LCA 13 (1) 49-56

Nielsen PH, Oxenbøll, Wenzel H (2007a): Cradle-to-Gate Environmental Assessment of Enzyme Products Produced Industrially in Denmark by Novozymes A/S. Int J LCA 12 (6) 432-438

Nielsen PH, Wenzel H (2007): Environmental Assessment of Ronozyme® P5000 CT Phytase as an Alternative to Inorganic Phosphate Supplementation to Pig Feed Used in Intensive Pig Production. Int J LCA 12 (7) 514-520

Nielsen PH (2005): Life Cycle Assessment Supports Cold-Wash Enzymes. SÖFW-Journal 131 (10)

Nielsen PH, Nielsen AM, Weidema BP, Dalgaard R, Halberg N (2007b): LCA Food Database, available online at www.lcafood.dk

OECD/FAO (2006): OECD-FAO Agricultural Outlook 2006-2015. OECD Publishing

Palliére C (2007): Written dialogue with Christian Palliére, director, Agriculture and Environment, European Fertilizer Manufacturers Association, Belgium

Rauer J (2007): Written dialogue with Jannik Rauer, consultant, Danish Plant Directorate, sector for environment, Denmark

Ramankutty N, Foley JA (1999): Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global Biogeochemical Cycles 13 (4) 997-1027

Ramankutty N, Foley JA, Olejniczak NJ (2002a): People on the Land: Changes in Global Population and Croplands during the 20th Century. Ambio 31 (3) 251-257

Ramankutty N, Foley JA, Norman J, McSweeney K (2002b). The global distribution of cultivable lands: current patterns and sensitivity to possible climate change, Global Ecology & Biogeography 11, 377-392.

Ramankutty N, Evan AT, Monfreda C, and Foley JA (2007): Farming the Planet: 1. Geographic distribution of global agricultural lands in the year 2000, Global Biogeochemical Cycles, doi:10.1029/2007GB002952, in press.

Schmidt (2007): System delimitation in agricultural consequential LCA – Outline of methodology and illustrative case study of wheat in Denmark. Int J LCA (accepted)

Skals PB, Krabek A, Nielsen PH, Wenzel H (2007): Environmental assessment of enzyme assisted processing in pulp and paper industry. Int J LCA, DOI: http://dx.doi.org/10.1065/lca2007.11.366

Thiesen J, Christensen TS, Kristensen TG, Andersen RD, Brunoe B, Gregersen TK, Thrane M, Weidema BP (2006): Rebound Effects of Price Differences. Int J LCA, DOI: http://dx.doi.org/10.1065/lca2006.12.297

Thum O, Oxenbøll KM (2008): Biocatalysis – A Sustainable Method for the Production of Emollient Esters. SÖFW-Journal 134 (1/2) 44-47

Tribus M, El-Sayed Y (1982): Introduction to Thermoeconomics, Compendium, MIT

van Meijl H, van Rheenen T, Tabeau A, Eickhout B (2006): The impact of different policy environments on agricultural land use in Europe. Agriculture, Ecosystems and Environment 114, 21-38

Weidema BP (2003): Market Information in Life Cycle Assessment. Danish Environmental Protection Agency. Danish Ministry of Environment, Environmental Project No. 863

Wenzel H, Hauschild M, Alting L (1997): Environmental assessment of products. Volume 1: Methodology, tools and case studies in product development. Chapman and Hall.

Wenzel H (1998): Application Dependency of LCA Methodology: Key Variables and Their Mode of Influencing the Method. Int J LCA 3 (5) 281-288

13 Article Collection

This chapter contains the scientific papers written during the PhD project. The list below presents an overview.

1. Kløverpris J, Wenzel H, Nielsen PH (2008): *Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption Part 1: Conceptual Analysis and Methodological Proposal*. International Journal of LCA 13 (1) 13-21.

2. Kløverpris J, Baltzer K, Nielsen PH (2008): *Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption Part 2: Example of wheat consumption in Brazil, China, Denmark, and the USA*. International Journal of Life Cycle Assessment 15, 90-103.

3. Kløverpris J (2008): *Identification of biomes affected by marginal expansion of agricultural land use induced by increased crop consumption*, Journal of Cleaner Production 17, 463-470.

13.1 Article 1: LCI Modelling of Land Use – Part 1

Kløverpris J, Wenzel H, Nielsen PH (2008): *Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption Part 1: Conceptual Analysis and Methodological Proposal*. International Journal of LCA 13 (1) 13-21.

Land Use in LCA (Subject Editor: Llorenç Milà i Canals)

Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption

Part 1: Conceptual Analysis and Methodological Proposal *

Jesper Kløverpris[1,3]*, Henrik Wenzel[2] and Per H. Nielsen[3]

[1] Technical University of Denmark, Department of Manufacturing Engineering and Management, Section for Innovation and Sustainability, Produktionstorvet 424, 2800 Lyngby, Denmark
[2] University of Southern Denmark, Institute of Chemical Engineering, Biotechnology and Environmental Engineering, Niels Bohrs Allé 1, 5230 Odense M, Denmark
[3] Novozymes A/S, Krogshøjvej 32, 2880 Bagsværd, Denmark

* **Corresponding author** (jk@ipl.dtu.dk)

DOI: http://dx.doi.org/10.1065/lca2007.10.364

Please cite this paper as: Kløverpris J, Wenzel H, Nielsen PH (2007): Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption. Part 1: Conceptual Analysis and Methodological Proposal. Int J LCA 13 (1) 13–21

Preamble. The present paper is the first in a series of two. The paper addresses the conceptual aspects of modelling global agricultural land use for LCI. Based on the outlined concepts, the second paper presents a practical example of global land use modelling.

Abstract

Background, Aims and Scope. The actual land use consequences of crop consumption are not very well reflected in existing life cycle inventories. The state of the art is that such inventories typically include data from crop production in the country in which the crop is produced, and consequently the inventories do not necessarily consider the land ultimately affected in the systems being studied. The aims of this study are to analyse the mechanisms influencing the long-term land use consequences of changes in crop demand and to propose a methodological framework for identifying these consequences within a global scope.

Materials and Methods. The study refers to the principles of consequential LCA, which means that the consequences of changes in consumption are studied from a market-based perspective. In this context, the study addresses the feasibility of using economic modelling to identify ultimate land use consequences of crop consumption.

Results. Based on the current market trend for crops and an analysis of basic mechanisms in crop production, concepts for modelling how crop consumption affects the global agricultural area and the intensity of crop production are suggested. It is demonstrated how the assumptions concerning drivers for technological development have a profound influence on identification of the marginal response to crop consumption, and how the geographical location of crop consumption also influences the composition of the marginal production response in terms of cropland expansion and intensification.

Discussion. Crop prices have been falling at a global scale and are projected to decline further. At the same time, crop yields per hectare are continuously increasing. This indicates that drivers other than crop demand have a strong influence on technological development in crop production.

Conclusions. Economic modelling in combination with geographical information and agricultural statistics can be used to estimate long-term land use consequences of changes in crop consumption. The GTAP Model is a suitable tool although it requires implementation of land supply curves, adjustment of elasticities to reflect long-term changes, and possibly establishment of a link between crop demand and technological development. Through this approach, life cycle inventories for crops reflecting the actual land use consequences of consumption can be established.

Recommendations and Perspectives. Further work (based on the methodological framework in this study) will address the practical modelling of land use changes induced by crop consumption in different regions with the purpose of including this in LCI.

Keywords: Agriculture; consequential LCA; crops; GTAP (Global Trade Analysis Project); land use; marginal production

Introduction

For centuries, mankind has expanded the global agricultural area (pastures and croplands) in order to grow crops and raise livestock. As **Fig. 1** shows, this trend continued up to

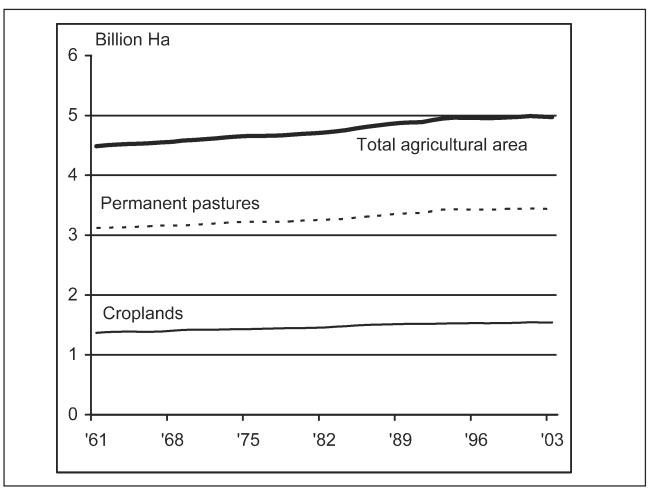


Fig. 1: Global development of croplands, permanent pasture and total agricultural area from 1961 to 2003. FAOSTAT (2007)

* **ESS-Submission Editor:** Dr. Llorenç Milà i Canals (L.MiC@surrey.ac.uk)

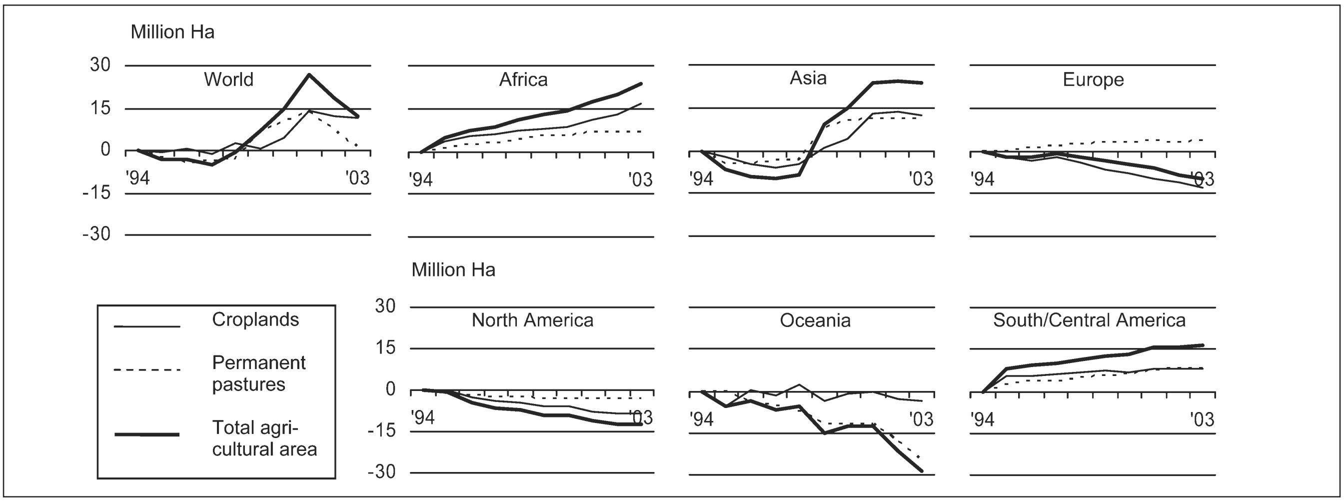


Fig. 2: Regional development of croplands, permanent pastures and total agricultural area from 1994 to 2003. Reference year: 1994. FAOSTAT (2007)

the middle of the 1990s. Since then, the increase has been very modest. However, as shown in **Fig. 2**, different regional trends in agricultural areas can be observed. One of several factors influencing these trends is crop demand. Any purchase and consumption of crops will influence the global agricultural area, and these land use effects should be included in LCA. This is generally acknowledged, but there is still no consensus on how to do it. Some research has focused on land use impact assessment (Lindeijer 2000, Mila i Canals et al. 2007), but few have looked at its precondition, namely the identification of the land actually affected in the systems under study. As demonstrated by Kløverpris (2006), this element is crucial for the validity and credibility of an LCA in which land use aspects are involved. In such studies, inventory data from the *direct crop suppliers* (farmers producing the crops used in the relevant life cycle) is often used. However, this does not necessarily reflect the actual consequences of crop consumption in markets involving international trade as crop markets typically do. Increased crop demand leads to increased production and, if production cannot be increased in the country or region in question, production will be increased elsewhere. The question is where and how. The location in which crop production is increased and the ways in which it is increased (intensification or cropland expansion) are decisive for the environmental impacts of crop consumption.

Weidema (2003) suggests a general approach to identifying the marginal/most sensitive supplier, suggesting that the supplier or technology most sensitive to changes in demand in the long run will be the one with the lowest (long-term) production costs (under certain conditions). This general principle, however, needs more detailed understanding for crop production, which is characterised by literally millions of suppliers and a sliding transition between low-tech and high-tech agriculture. Furthermore, production costs do not include transport costs and possible tariff costs, which also affect the competitiveness of crop suppliers.

The purpose of this paper is to present a conceptual analysis of crop production and the mechanisms determining land use consequences of changes in the demand for specific crops. Based on this analysis, a method will be proposed to quantify these land use changes and determine their geographical location in order to include them in life cycle inventories for crop consumption.

The term *marginal crop production* will be used to designate changes in crop production resulting merely from changes in crop demand. In other words, marginal crop production is the marginal production response to consumption of a given crop.

The agricultural term *marginal land* is commonly used to describe the farm land being brought into production last and abandoned first because it is likely to give a poor return. In this sense, marginal crop production is not so different (except for a larger geographical scale) because it is the last amount of crops produced or the crops that were not produced due to decreasing demand.

As the alternative to crop consumption is no consumption (or consumption of something else), the decision to consume crops will, seen in isolation, increase the demand for crops. The term *crop consumption* will therefore be used synonymously with *increased demand for crops* throughout this paper.

1 Scope

The study considers all types of crop consumption except those of a magnitude which is large enough to change the structure and trend of the global crop market.

Geographical scope: Major crops such as wheat, maize and rice are traded on the global market. Changes in crop demand may therefore, in principle, have consequences anywhere in the world and a global scope is applied in the study.

Temporal scope: The study addresses long-term land use consequences of crop consumption taking place in the existing market for crops. However, it is assumed that the full effects of crop consumption occur instantaneously under the conditions of the present market mechanisms. This is a common assumption in LCA, although the full effect will be revealed over a period of time.

Technological scope: In accordance with the assumption of instantaneous adaptation to changes in crop demand, production with present agricultural technology is assumed (unless demand affects the technological development, see Section 2.8).

Methodological scope: The study builds on the consequential approach to system modelling in LCA, which is generally characterised by the analysis of consequences caused by a given change or decision (Wenzel 1998, Ekvall and Weidema 2004). In consequential LCA, marginal data is used in the life cycle inventory (Weidema et al. 1999) and system expansion is used in the event of co-product and reuse/recycling/recovery issues. As discussed in Mila i Canals et al. (2006), the consequential approach to land use system modelling solves the long-known problem of transformation allocation between subsequent land use activities (see e.g. Lindeijer et al. 2002) by considering the market situation of crop production.

2 Analysis of the Mechanisms Determining Land Use Consequences of Marginal Crop Production

To determine the marginal response to crop consumption, it is necessary to identify and analyse the mechanisms that influence the consequences of changes in crop demand.

2.1 Long-term supply elasticity of crops

In competitive markets with no constraints on production factors, long-term prices are not determined by demand but by the long-term production costs, implying perfectly elastic supply (Weidema 2003). This means that, in the long run, an increased demand will be met by an equal increase in production (**Fig. 3**). This assumption is often implicitly used in LCA but the question is whether it is valid for crops. According to Abler (2003), intermediate inputs to crop production (fertilisers, pesticides, etc.) are presumed to be unconstrained and Bruinsma (2002) states that the world is not approaching shortages of suitable agricultural land at the global level (despite regional shortages). Apparently, this implies that the global supply of crops is perfectly elastic. However, that is not necessarily the case as differences in land fertility may cause differences in production costs. Furthermore, transportation and trade costs are also affecting crop prices (see Section 2.9).

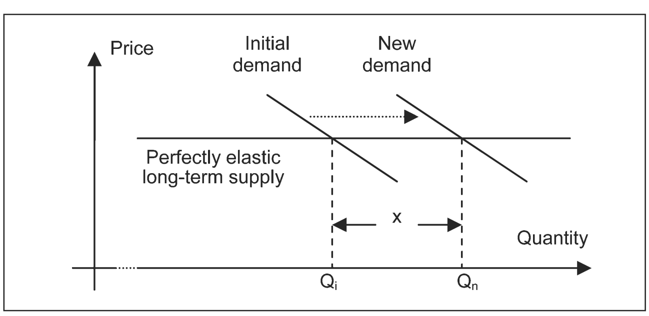


Fig. 3: General illustration of a perfectly elastic long-term supply in which the price equals the long-term production costs. If the demand increases by x, the demand curve will move to the right (as indicated by the dashed arrow) and the increase in the quantity produced will also be x ($Q_n - Q_i$)

2.2 Basic mechanisms in crop production

Global crop production is increasing due to population growth, increasing incomes in large Asian economies, and increased application of crops for non-food purposes, especially biofuels (OECD/FAO 2006). Basically, there are three main mechanisms to increase the production of a specific crop:

1. *Displacement* of other crops
2. *Expansion* of croplands
3. *Intensification* of existing production

Although these mechanisms have all been expressed as ways to *increase* production, the inverse of displacement, expansion and intensification can, in principle, be used for the opposite purpose.

2.3 Relationship between crop consumption and land use changes

In a growing global market, crop consumption will further increase the demand for crops. In the short term, increased demand for a specific crop *i* will lead to increased prices. Suppliers (farmers) will thus have incentives to produce more of crop *i*. They can do this by displacement, expansion and/or intensification. Suppliers closer to the consumer will benefit more due to lower transportation costs. Likewise, suppliers with easy access to the market in terms of low or no tariff payments will be more likely to cover the increased demand. These suppliers (and possibly also some in a less advantageous position) will respond to the increased demand for crop *i*. To the extent that displacement is used to cover this demand, the supply of other crops will decrease and, in the short term, prices will increase. This will give other farmers incentives to produce more of these crops (or substitutes). This mechanism is designated *replacement* (of the crops displaced to begin with). Besides expansion and intensification, replacement may also involve new displacement (and subsequent replacement) and, consequently, the effects of the initial crop consumption will trickle through the global agricultural system. This chain of events will continue until it reaches suppliers only responding with expansion and/or intensification (and no displacement). At this point, production and prices will stabilise and a new economic equilibrium will emerge. The land use change resulting from the initial consumption of crop *i* will be the sum of expansion that has taken place through the process.

2.4 Displacement

To the extent possible, displacement will occur whenever it becomes more profitable to produce one crop than others. This will happen when the demand for specific crops changes. However, farmers cannot choose freely to produce one crop rather than another since several constraints apply. These are constituted by climate conditions, soil properties and crop rotation schemes. Furthermore, farmers need to grow several crops in order to limit economic consequences of possible harvest failure. In some regions of the world, displacement may be the only option for responding to changes in demand. If farmers are not able to expand or intensify production (due to regulations or other constraints), they can only adjust to changing market conditions by planting the most profitable mix of crops. In such cases, the marginal land use consequences of crop consumption will be found in other regions due to the displacement-replacement mechanism discussed above.

2.5 Expansion of croplands

Expansion of croplands is an intuitively obvious mechanism for increasing crop production. This process typically takes place at the expense of nature, but may also occur on land already transformed, e.g. due to timber production (Lambin and Geist 2003). Expansion is therefore a special case of *transformation*, which is the term generally used in LCA for conversion of one type of land use to another. With regard to marginal crop production, this study defines expansion as a process relative to the ongoing trend in cropland area. Expansion can, therefore, in principle, also be constituted by delayed release of croplands (**Fig. 4**).

According to FAOSTAT (2007), global croplands have increased by approximately 13% (more than 170 million hectares) since 1961 (see Fig. 1), and in this study increased crop demand is assumed to be the main driver. Interestingly, croplands in Europe and North America have been slightly decreasing in recent years despite increasing global crop demand (see Fig. 2). There may be several explanations for this, including subsidised afforestation, expansion of infrastructure and cities, more demand for recreational areas, and (not least) changes in agricultural policies. Besides that, the options for cropland expansion in parts of Europe (and some other regions) are limited simply because most suitable land has already been brought into production during centuries of agricultural expansion. This means that countries in such regions face physical (and possibly also regulatory) cropland constraints. Meanwhile, yield increases per hectare (intensification) continuously reduce the need for cropland expansion, but apparently not enough to prevent it from happening in Africa, South/Central America and, to some extent, Asia (see Fig. 2).

2.6 Intensification of existing production

In the middle of the twentieth century, intensive agricultural research was funded by private foundations and national governments because of threatening food shortages. This led to dramatic increases in annual crop yields and became known as the green revolution (IFPRI 2002). Since 1961, world food production has doubled (Ramankutty et al. 2006), while the global agricultural area has only increased by roughly 10% (see Fig. 1), meaning that the remaining 90% or so of the increased food production came from intensified production. This emphasises the importance of intensification and the need to consider it in the analysis of marginal crop production. Intensification has been divided into two subgroups, namely *optimisation of production* and *technological development*.

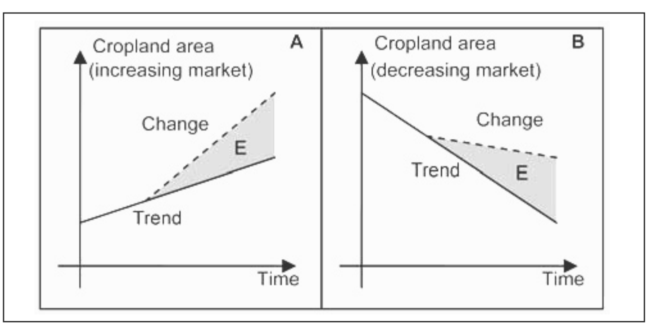


Fig. 4: Cropland expansion (E) derived from marginal crop production can either take the form of accelerated expansion in an increasing market (A) or delayed release of croplands in a decreasing market (B). In both situations, the expansion is the difference between the existing trend (business as usual) and the change resulting from the increased demand for crops

2.6.1 Optimisation of production

Farmers can intensify crop production by increasing -

- Fertiliser application
- Pesticide application
- Irrigation level
- Cropping intensity[1]

However, these options are subject to diminishing returns: the higher the level of fertiliser, pesticide and/or water application on a given field, the lower the increase in yield per unit of input (**Fig. 5A**). The reason why cropping intensity is also subject to diminishing returns is that increased cropping intensity requires increased inputs of fertilisers, pesticides and water.

Due to the diminishing returns, there is an optimum level for the four optimisation options. The optimum is determined by the largest difference between the value of production (yield multiplied by crop price) and the production costs, which are linearly related to the input level (**Fig. 5B**). If the prices of crops or inputs change, farmers will adjust the application levels. Therefore, agricultural (price) support leads to intensified production. However, regulatory constraints may apply to application of fertilisers, pesticides and irrigation. For example, many EU countries have imposed a limit on yearly organic N fertilisation of 170 kg/ha (European Commission 2002). Typically, the use of pesticides is also regulated because of their toxicological properties. Furthermore, irrigation restrictions may apply in some regions, especially where water is scarce. Finally, there is an upper limit to cropping intensity set by climatic conditions.

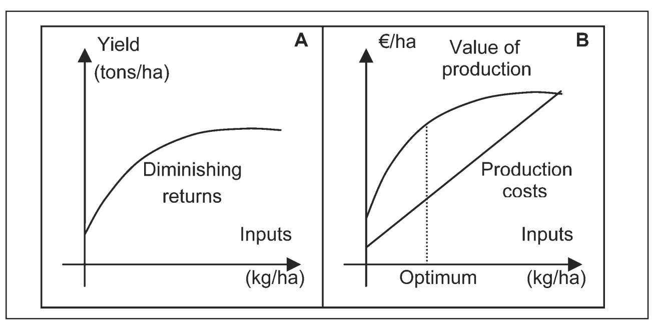


Fig. 5: Relationship between inputs and yield per hectare at a given technological stage (A) and the implications for profit optimisation (B). The optimum level of inputs is characterised by the largest difference between production costs and value of production (yield multiplied by crop price)

[1] The ratio between harvested area per year and the area of arable land (Bruinsma 2002).

2.6.2 Technological development

Intensification can also be achieved through technological development to essentially improve

- Mechanical aids
- Crop strains
- Agricultural practices

As opposed to the optimisation mechanisms, which can also be used to lower yields per hectare in the case of decreasing demand, the technological development within the three areas mentioned above will always lead to increased annual crop yields per hectare simply because technological improvements are not discarded in case of falling prices.

Adoption of technological improvements occurs automatically as long as they offer lower production costs. This can be explained by the theory of *the agricultural treadmill* put forward by Cochrane (1958): a small group of innovative farmers will adopt new technologies early and, consequently, increase their production capacity and market share. Since they only constitute a small fraction of the suppliers, prices will remain relatively unchanged. However, when the larger group of less innovative farmers realise the benefits of the new technology, their adoption will cause a significant supply increase, resulting in falling prices. The non-adopters will be the losers because their production costs remain the same while prices fall (Gabre-Madhin et al. 2002). The agricultural treadmill demonstrates how new technology is adopted regardless of demand changes.

Control of technological development is beyond farmers. Agricultural machinery is developed by private companies, which is also the case for improved crop strains, although some of this development takes place in public research institutions (Andersen 2006). Development of improved agricultural practices is an international research field primarily based in public research institutions (Andersen 2006).

Drivers of technological development: The main driver for the development of better mechanical aids for crop production is assumed to be internal competition between suppliers of agricultural machinery. However, it cannot be ruled out that increased crop demand will also influence the speed of technological development within this field. The general drivers for the development of better crop strains are assumed to be crop demand and internal competition between companies developing and selling seeds. The demand for crops will influence the research priorities within these companies. More resources will be allocated to the crops in high demand because these are being sold in large quantities. Furthermore, public funds may be allocated to this field of research in case of existing or perceived future societal food shortages. This can also be considered a type of demand. Meanwhile, internal competition between seed providers will also drive the development of better crop strains. The general drivers for development of better agricultural practices will mainly be political decisions since this is mainly a public research field. This means that societal needs may also influence this development just as for crop strain development. In summary, crop demand has a certain influence on technological development, but other factors such as internal competition between commercial developers also play a role.

2.6.3 Interrelation between optimisation and technological development

At a given technological stage (see Fig. 5A), optimisation will be determined by two factors, namely crop prices (determining the value of production) and the prices of fertilisers, pesticides, irrigation and other inputs determining production costs (see Fig. 5B). However, seen over a period of time, a third factor will influence optimisation, namely technological development, which will move the curve in Fig. 5A upwards and tend to stretch it out. This means that the crop yield per hectare related to a given input level will increase over time, while crop prices will decrease due to the lower costs per unit of output (see Section 2.1). The changes in crop prices and yield will affect the value of production (in opposite directions), and consequently the optimum application of inputs (see Fig. 5B). This illustrates how technological development has a profound impact on optimisation.

2.7 Composition of marginal crop production

Based on the analysis of displacement, expansion and intensification, a mathematical description of marginal crop production (demand driven by definition) can be derived. As displacement is only an intermediate process (see Section 2.4), changes in global crop production will ultimately stem from expansion and intensification. As discussed previously, cropland expansion is assumed to be driven by demand, whereas intensification may be partly driven by other factors. This means that the continuous increase in global crop production (ΔQ), which has been observed over several decades, can be divided into three parts (**Eq. 1**).

$$\Delta Q = \Delta Q_A + \Delta Q_I = \Delta Q_A + \Delta Q_{I,d} + \Delta Q_{I,o} \tag{1}$$

where

ΔQ_A is the change in production caused by change in cropland area

ΔQ_I is the change in production caused by change in intensity

$\Delta Q_{I,d}$ is the change in production caused by change in intensity driven by demand

$\Delta Q_{I,o}$ is the change in production caused by change in intensity driven by factors other than demand

Changes in crop production can also be expressed in terms of area and yield per hectare:

$$\Delta Q_A = Y \cdot \Delta A \tag{2}$$

$$\Delta Q_I = \Delta Y\ (A + \Delta A) \tag{3}$$

where

Y is the initial average crop yield per hectare

ΔA is the change in cropland area

ΔY is the change in average crop yield per hectare

A is the initial cropland area

If a is the fraction of intensification driven by demand, marginal crop production (ΔQ_m) can be described as

$$\begin{aligned}\Delta Q_m &= \Delta Q_A + \Delta Q_{I,d} = \Delta Q_A + a \cdot \Delta Q_I \\ &= Y \cdot \Delta A + a \cdot \Delta Y\ (A + \Delta A)\end{aligned} \tag{4}$$

2.8 Significance of the relationship between demand and technological development

It is difficult to estimate the fraction of intensification derived solely from increased demand (a in **Eq. 4**). However, the significance of the relationship between demand and technological development with regard to marginal crop production can be demonstrated on the assumption of a perfectly elastic (long-term) supply of crops. This implies a fixed price at a given technological stage (see Fig. 3), ignoring the influence of transportation costs and possible tariffs related to the movement of crops (see Section 2.9). Under these conditions, only technological development will influence optimisation because it determines yield per unit of input (see Fig. 5) and, consequently, crop prices (see Section 2.1). In other words, intensification becomes synonymous with technological development because the latter inherently determines optimisation (still assuming perfectly elastic supply and costless movement of crops). Accordingly, a (in **Eq. 4**) becomes synonymous with the fraction of technological development driven by demand. The significance of the relationship between demand and technological development can therefore be analysed by assuming technological development to be fully driven by demand ($a = 1$) and completely driven by other factors ($a = 0$) respectively.

2.8.1 Technological development fully driven by demand

On the assumptions described in Section 2.8 and the additional assumption of technological development being fully driven by crop demand, no yield increases per hectare will be observed at a constant crop demand (conflicting with the theory of the agricultural treadmill). On the other hand, any increase in crop demand will lead to technological development and, consequently, higher yields per hectare. As no production increase occurs due to factors other than demand, marginal production becomes, by definition, synonymous with the total increase in production ($\Delta Q_m = \Delta Q = \Delta Q_A + \Delta Q_I$).

2.8.2 Technological development completely driven by factors other than demand

If technological development is assumed to be driven completely by factors other than crop demand, changes in crop demand will not affect the rate of crop yield increases per hectare (intensification) on the assumptions described in Section 2.8. This means that marginal crop production will only come from cropland expansion ($\Delta Q_m = \Delta Q_A$), which may partly be constituted by delayed release of cropland for other purposes (see Fig. 4).

2.9 Significance of the geographical location of crop consumption

As shown above, the relationship between technological development and crop demand has important implications for the composition of marginal crop production. The same is true for the geographical location of crop consumption (the physical origin of demand). The reason is that, besides production costs, the crop price paid by the buyer also includes transportation and possible trade costs in the form of tariffs. Therefore, it may sometimes be more profitable to pay local farmers (possibly without options for expansion) to intensify production (through the use of fertilisers, pesticides and/or irrigation) rather than buying crops from distant suppliers with lower production costs. This means that, even if technological development is considered to be completely unrelated to crop demand (see Section 2.8.2), intensification may still contribute to marginal crop production. This is because the price increases related to transportation and trade influence optimisation (see Fig. 5). Be aware that this price increase is not related to production costs. Even if all production factors in crop production are unconstrained (see Section 2.1), the supply of crops in a given location will not necessarily be perfectly elastic (fixed price in the long run at a given technological stage) because of the transport and trade issues. Increased crop demand will therefore lead to higher prices in areas with constraints on croplands and/or intensification options.

Some countries have removed or reduced the trade barriers between them by forming trade agreements or trade blocs of varying economic integration. This means that crops will flow more freely between these nations. Furthermore, some countries and trade blocs provide preferential access to their markets for developing countries. For example, the EU forms a preferential trading area for the African, Caribbean and Pacific countries and provides duty-free access to all products except weapons (plus sugar and rice up to 2009) from the Least Developed Countries (European Council 2001). These different trade arrangements influence crop flows in the market and may cause neighbouring countries to choose completely different crop suppliers simply because they belong to different trade blocs. Again, this illustrates why the geographical location of crop consumption influences the composition of marginal crop production.

3 Method Proposal for Identification of Land Use Consequences related to Marginal Crop Production

Based on the conceptual outline and analysis presented in Section 2, a proposal for an operational method for identification of land use changes related to marginal crop production is presented in this section.

3.1 Economic modelling of changes in crop demand

Some of the issues related to identification of marginal crop production can be handled by economic models developed to simulate the economic mechanisms of society. Jensen and Andersen (2003) have used a partial equilibrium (PE) model of the Danish agricultural sector to identify marginal suppliers of various agricultural products within the country. However, they assumed a fixed national area of croplands and did not consider displaced crops or import/export effects. To include these aspects, a global model is required with a sufficient number of regions and agricultural sectors. In van Meijl et al. (2006), three global PE models considering the mobility of land in and out of agricultural production are discussed, namely the FAO World Food Model, the FAPRI Model, and the Penn State Trade Model. Either of these models may be suitable for identification of marginal crop production although a disadvantage of PE models is that they do not take into account the interaction between the agricultural sectors and the remaining part of the world economy.

The Global Trade Analysis Project (GTAP) has developed a general equilibrium model in agreement with the principles of neoclassical economic theory. GTAP also maintains a database representing the global economy (87 regions with 57 sectors each). Primary production factors (capital, labour and land) are constrained in the model, and the interaction between sectors and regions is based on economic input-output databases, elasticities of supply and demand (empirically estimated or calibrated by the model), international trade regulations, and trade agreements (bilateral and multilateral). The economic consequences of a change (in demand, supply, policy, etc.) can be studied by introducing a so-called 'shock', e.g. a region-specific change in crop demand. The result is a new economic equilibrium with all changes expressed in relative terms. For further details, see Hertel (1997) or Klijn and Vullings (2005).

The fact that the GTAP Model reflects the entire global economy makes it well suited for the analysis of global consequences of changes in crop demand. The inclusion of trade agreements and regulations as well as a global transport sector reflecting the costs of transportation makes it possible to include geographical dependency in the analysis of changes in crop demand. Furthermore, the standard GTAP Model includes eight crop sectors and four livestock sectors, which are all using land as a primary production factor. Due to the elasticities incorporated in the model, it is possible to study the interaction between the different agricultural sectors when the demand in one of them is changed. Furthermore, it is also possible to study effects in other sectors.

3.1.1 Applying the GTAP Model to land use LCI modelling

Although the GTAP Model offers advantages for the establishment of land use inventory data for marginal crop production, the standard version also suffers from some weaknesses in this respect. However, most of these problems can be solved by modification of the model or informed interpretation of the results.

Land supply: The availability (supply) of land is constant in the standard GTAP Model. This means that shocking the demand for a specific group of crops will only result in displacement and intensification. However, van Meijl et al. (2006) have proposed the integration of so-called land supply curves in the GTAP Model, which will allow the use of agricultural land to be determined by the model. Expansion of the agricultural area can thus be estimated. Meanwhile, the construction of national or regional land supply curves requires data on the available amount of unutilised cultivable land (see Section 3.2).

Inputs to crop production: The GTAP Model mainly builds on economic theory and not so much on biophysical cause-effect mechanisms. For example, primary production factors (capital, labour and land) can substitute for one another, but intermediate inputs to production of goods are locked in a fixed nesting structure. This means that the proportions between intermediate inputs are constant. In other words, crop production cannot be optimised by adjusting the application of fertilisers alone, but only by adjusting all inputs equally. Bear in mind that land is considered a primary production factor and, consequently, it is not subject to the fixed nesting structure. This means that the model can calculate whether, and to what extent, expansion is more profitable than intensification (if the land supply curves mentioned above, or similar mechanisms, are implemented).

Time perspective and elasticities: The elasticities in the GTAP database do not necessarily reflect the long-term perspective typically applied in LCA. This data should therefore be adjusted. In particular, the so-called Armington elasticities expressing the inertia of changing trade patterns should be changed in order to allow for a full adjustment to the studied changes in crop demand.

Technological development: In the standard GTAP Model, the technological stage is assumed to be fixed. However, technological development can be incorporated either as an independent variable (determined outside the model) or as a function of another variable, e.g. crop prices. This decision depends on the assumption regarding the relationship between crop demand and technological development (see Section 2.8).

Conversion of relative changes to quantities: The fact that the GTAP Model expresses results as relative changes means that a conversion of the results is necessary to provide them in physical units such as mass of production and area of agricultural land use for LCI. This is possible using data from FAOSTAT (2007), but it requires a grouping of the FAOSTAT crops corresponding to the GTAP crop sectors.

Level of detail: The GTAP Model is quite coarse, which means that it does not contain detailed information about specific countries. For example, region-specific or country-specific limits on fertiliser application are not (by default) incorporated in the model. Such information must be included as ad hoc adjustments to the model or, alternatively, must be accounted for in the interpretation of the GTAP results when the composition of marginal crop production is analysed.

3.2 Utilising geographical information about land use and land use changes

Without the integration of the mentioned land supply curves (or a similar mechanism) in economic modelling, it is not possible to include the expansion aspect of marginal crop production in the modelling. As the construction of land supply curves is dependent on quantitative data on unutilised cultivable land, geographical information becomes vital to the assessment. Furthermore, qualitative information about current land use changes can be used to validate and supplement the results from the economic modelling. A consistency check can then be made to see if land use changes are actually taking place in the regions where cropland expansion is predicted to occur by the economic modelling. Information on current land use changes can also be used to identify the biotopes transformed in the regions affected. Finally, other types of information about current and future land use changes can be used. For instance, Bruinsma (2002) states that more than 80% of the future expansion in arable area is expected to take place in sub-Saharan Africa and Latin America, which conforms well with Fig. 2.

4 Results

This study has identified the main aspects of importance for LCI modelling of land use changes induced by crop consumption and has proposed a framework in which these complex issues can be handled simultaneously, namely economic modelling combined with geographical information. Depending on choices of assumptions regarding long-term supply elasticity and drivers for technological development, the result will come out as production changes in a number of regions in which some production will derive from intensification and some from expansion. The latter will involve transformation of natural areas, which can be quantified via data from FAOSTAT (2007). In other words, the results will provide an estimate of the actual land use changes induced by crop consumption. This information can be included in life cycle inventories – thereby providing the precondition for land use impact assessment.

5 Discussion

In the considerations regarding crop demand and technological development (see Section 2.8), the development in crop prices might contain useful information about the relationship between the two. As discussed previously, agricultural production has been intensified substantially since the 1960s. In the meantime, producer prices for crops have been falling on a global scale (Gabre-Madhin et al. 2002). This might indicate that technological development is driven by factors other than demand since price increases cannot explain the intensification. However, it must be kept in mind that the EU, the USA and others have paid considerable subsidies to their farmers for several decades. This has given these farmers incentives to intensify production (by use of fertilisers, pesticides and irrigation), and it has enabled them to sell their crops at a low price. In other words, technological development is not the only factor that has influenced producer prices in recent decades. However, it is not likely that agricultural support in itself can sustain a continuous decrease in producer prices unless the support is gradually increased, which is not the case nowadays. Nevertheless, real prices for agricultural commodities will continue to fall in the near-term future (OECD/FAO 2005). This is because the mechanisms strengthening supply, which are mainly productivity gains (technological development), seem to be stronger than the mechanisms strengthening demand, e.g. income and population growth (see **Fig. 6** for a conceptual illustration). It does, therefore, indeed seem that technological development in crop production is driven by other factors than crop demand, e.g. internal competition between developers of new crop strains and mechanical aids (see Section 2.6.2). It is also worth noticing that crop yields per hectare are generally projected to increase worldwide within the next 10 years (FAPRI 2006) despite the falling prices. Still, it cannot be ruled out that increased demand for crops will result in additional technological development in crop production, although this influence might be small compared to that of internal competition between suppliers of mechanical aids and seeds.

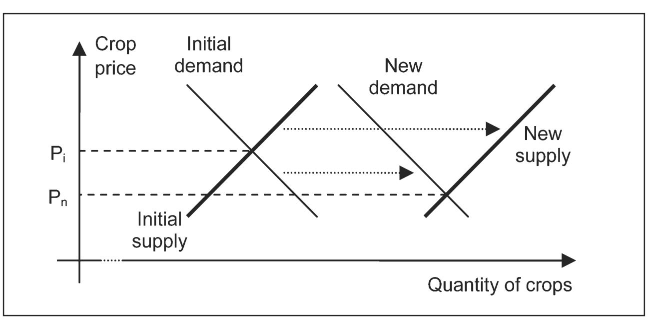


Fig. 6: Illustration of decreasing crop prices. Since the supply curve moves further to the right than the demand curve (movement indicated by dashed arrows), the new crop price (P_n) is lower than the initial crop price (P_i)

In agreement with the purpose of the present paper, the main focus has been on land use changes, i.e. the area(s) transformed (land type and geographical location) as a result of crop consumption in a given region. Meanwhile, the other side of marginal crop production, namely demand-driven intensification (optimisation) must also be accounted for in LCA. Although this lies beyond the scope of the present paper, a brief discussion of the issue follows: Part of the results from a GTAP simulation is the relative changes in intermediate inputs to sectors. For instance, if the demand for wheat increases by x tons in a given region, the intermediate inputs to the oilseed sector in a neighbouring region may increase by 1 percent due to the displacement-replacement mechanisms. The intermediate inputs include fertilisers, pesticides, fuel, water and other inputs to be listed in the LCI. A disadvantage of the GTAP Model is that some of these inputs (e.g. fertilisers and pesticides) belong to the same sector (and consequently cannot be separated out). Therefore, it is necessary to couple the GTAP results with more fine grained information on inputs to crop production, e.g. national agricultural statistics. If such information is not available for individual crop sectors in the relevant regions, it might be necessary to calculate a weighted average of the change in intermediate inputs to all crop sectors in a region. When the initial inputs to crop production are known and the relative changes in inputs are given by the GTAP Model, it is possible to calculate the increased inputs used for intensification and list them in the LCI.

6 Conclusions

Increased production of specific crops can be achieved by displacement, expansion and intensification. Displacement will lead to replacement and, ultimately, the marginal response to crop consumption will be a combination of expansion and intensification. The latter can be achieved through optimisation (application of fertilisers, pesticides and irrigation) or technological development (improved mechanical aids, crop strains and agricultural practices). Assumptions concerning drivers for technological development have important implications for identifying the composition of marginal crop production. Furthermore, the geographical origin of crop consumption influences the marginal production response since transportation and trade costs might make intensification more attractive than imports in regions without possibilities for cropland expansion. The marginal response to crop consumption, including geographical dependency, can be estimated using economic modelling. In the GTAP Model, results will come out as relative changes in regional production and agricultural areas. These results can be converted to physical units using agricultural statistics, and their validity can be tested by comparing to geographical information on current land use changes. This will enable impact assessment of land use in LCA reflecting the actual consequences of crop consumption. Decision makers will thereby be able to consider the environmental impacts of the land use changes in other regions caused by the decisions taken in their own region.

7 Recommendations and Perspectives

Further work will address the practical modelling of long-term marginal responses to consumption of different crops in different regions of the world using the GTAP Model. Furthermore, an analysis will be made of the extent to which the magnitude of consumption influences the result in terms of the ratio of intensification to expansion as well as the distribution of regions affected. The findings of this work will be published in Kløverpris et al. (in prep).

Acknowledgements. The authors are grateful to Bo Weidema, 2.-0 LCA consultants and Kenneth Baltzer, University of Copenhagen, Faculty of Life Sciences, Institute of Food and Resource Economics, Denmark for valuable inputs and discussion.

References

Abler D (2003): Adjustment at the Sectoral Level. In: An IAPRAP Workshop on Policy Reform and Adjustment, The Wye Campus of Imperial College, October 23–25, http://agadjust.aers.psu.edu/Workshop_files/Abler_presentation.pdf

Andersen SB (2006): Written dialogue with Sven Bode Andersen, Professor of plant breeding. Faculty of Life Sciences, Denmark

Bruinsma J (ed) (2002): World Agriculture: Towards 2015/2030: an FAO Perspective. Earthscan, London

Cochrane WW (1958): Farm Prices – Myth and Reality. University of Minnesota Press

Ekvall T, Weidema B (2004): System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. Int J LCA 9, 161–171

European Commission (2002): Implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Luxembourg: Office for Official Publications of the European Communities

European Council (2001): Applying a scheme of generalised tariff preferences for the period from 1 January 2002 to 31 December 2004. Council Regulation (EC) No 2501/2001, Official Journal of the European Communities, L 346/1

FAOSTAT (2007): http://faostat.fao.org, United Nations Food and Agricultural Organisation

FAPRI (2006): U.S. and World Agricultural Outlook. Food and Agricultural Policy Research Institute, Iowa, USA

Gabre-Madhin E, Barret CB, Dorosh P (2002): Technological Change and Price Effects in Agriculture: Conceptual and Comparative Perspectives. International Food Policy Research Institute (IFPRI), Washington, DC, USA

Hertel TW (1997): Global Trade Analysis: Modeling and Applications. Cambridge University Press

Jensen JD, Andersen M (2003): Marginale producenter af udvalgte landbrugsprodukter. Institute of Food Economics, Danish Ministry of Food, Agriculture and Fisheries, working paper no. 08/2003 (in Danish)

Klijn JA, Vullings LAE (2005): The EURURALIS Study: Technical Document, EURURALIS 1.0 – A Scenario Study on Europe's Rural Areas to Support Policy Discussion. RIVM, Alterra-rapport 1196

Kløverpris J (2006): Inventory Analysis of Crop Production in LCA – A Pre-requisite for Impact Assessment of Crop Use. In: Milà i Canals L, Basson L, Clift R, Müller-Wenk R, Bauer C, Hansen Y, Brandão M (eds), Proceedings from Expert Workshop on Definition of Best Indicators for Biodiversity and Soil Quality for Life Cycle Assessment (LCA), Guildford, June 12–13. CES Working Paper 02/06, 50-53, available from www.surrey.ac.uk/CES

Kløverpris J, Baltzer K, Nielsen PH (in preparation): Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption. Part II: Example of wheat consumption in Brazil, China, Denmark, and the USA (to be submitted to Int J LCA)

Lambin EF, Geist HJ (2003): Regional Differences in Tropical Deforestation. Environment 45, 22–36

Lindeijer E (2000): Review of land use impact methodologies. J Clean Prod 8, 273–281

Lindeijer E, Müller-Wenk R, Steen B (2002): Impact Assessment of Resources and Land Use. Chapter 2 in: Life-Cycle Impact Assessment: Striving Towards Best Practice. Edited by Udo de Haes HA, Finnveden G, Goedkoop M, Hauschild M, Hertwich EG, Hofstetter P, Jolliet O, Klöpffer W, Krewitt W, Lindeijer E, Müller-Wenk R, Olsen SI, Pennington DW, Potting J, and Steen B. SETAC, Pensacola

IFPRI (2002): Green Revolution – Curse or Blessing? International Food Policy Research Institute, Washington, DC 20006-1002, USA

Mila i Canals L, Bauer C, Depestele J, Dubreuil A, Knuchel RF, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007): Key Elements in a Framework for Land Use Impact Assessment within LCA. Int J LCA 12, 5–15

Mila i Canals L, Clift R, Basson L, Hansen Y, Brandão M (2006): Expert Workshop on Land Use Impacts in Life Cycle Assessment (LCA). Int J LCA 11, 363–368

OECD/FAO (2005): OECD-FAO Agricultural Outlook 2005-2014, OECD Publishing

OECD/FAO (2006): OECD-FAO Agricultural Outlook 2006-2015, OECD Publishing

Ramankutty N, Graumlich L, Achard F, Alves D, Chhabra A, DeFries R, Foley J, Geist H, Houghton R, Goldewijk KK, Lambin E, Millington A, Rasmussen K, Reid R, Turner BL (2006): Chapter 2, Global Land Cover Change: Recent Progress, Remaining Challenges, in Land Use and Land Cover Change: Local Processes, Global Impacts, edited by E. Lambin and H. Geist, Springer Verlag, New York

van Meijl H, van Rheenen T, Tabeau A, Eickhout B (2006): The impact of different policy environments on agricultural land use in Europe. Agriculture, Ecosystems and Environment 114, 21–38

Weidema BP (2003): Market Information in Life Cycle Assessment. Danish Environmental Protection Agency. Danish Ministry of Environment, Environmental Project No. 863

Weidema BP, Frees N, Nielsen AM (1999): Marginal Production Technologies for Life Cycle Inventories. Int J LCA 4, 48–56

Wenzel H (1998): Application Dependency of LCA Methodology: Key Variables and Their Mode of Influencing the Method. Int J LCA 3, 281–288

Received: March 3rd, 2007
Accepted: October 28th, 2007
OnlineFirst: October 29th, 2007

13.2 Article 2: LCI Modelling of Land Use – Part 2

Kløverpris J, Baltzer K, Nielsen PH (2010): *Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption Part 2: Example of wheat consumption in Brazil, China, Denmark, and the USA*. International Journal of Life Cycle Assessment 15, 90-103.

Int J Life Cycle Assess (2010) 15:90–103
DOI 10.1007/s11367-009-0132-2

LAND USE IN LCA

Life cycle inventory modelling of land use induced by crop consumption

Part 2: Example of wheat consumption in Brazil, China, Denmark and the USA

Jesper Hedal Kløverpris · Kenneth Baltzer · Per H. Nielsen

Received: 5 April 2008 / Accepted: 16 October 2009 / Published online: 20 November 2009

Abstract
Background, aims and scope Most life cycle inventory data for crops do not include the ultimate (marginal) land use induced by crop consumption. The aims of this study were to present, document and discuss a method which can solve this problem and, furthermore, to present concrete examples for wheat consumption in Brazil, China, Denmark and the USA. A global scope is applied and the simulated adaptation to increased wheat demand corresponds to a long-term temporal scope under present market conditions with present technology.
Materials and methods The economic general equilibrium model, Global Trade Analysis Project (GTAP) is modified and applied. Agricultural statistics and a number of global land use and land cover datasets are used in the modification and the processing of the model output. Some of the land use datasets are processed by use of a geographic information system tool.
Results The net expansion of the global agricultural area per tonne of wheat consumed in Brazil, China, Denmark and the USA is estimated at 2,000, 260, 1,700, and 3,200 m^2, respectively. For Brazil, the expansion mainly affects tropical evergreen forest. For China and the USA, the expansion mainly affects boreal deciduous forest, savanna, open shrubland and tropical evergreen forest, and for Denmark, it mainly affects savanna, tropical evergreen forest and dense shrubland. The areas affected are quantified in the land use life cycle inventory (LCI) produced for the four countries.
Discussion The method applied allows for an even more detailed land use LCI than the one presented in this study. Results are influenced by existing global trade patterns and their inertia. Such aspects should be acknowledged in life cycle assessment (LCA). The method takes its starting point in consumption rather than production.
Conclusions The method presented makes it possible to simulate the main mechanisms of the global agricultural system and thereby construct an LCI containing the land use induced by crop consumption in a given region and the nature types (biomes) affected. The results are sensitive to changes in the so-called Armington elasticities representing the inertia of global trade patterns. It is considered reasonable to double the standard elasticities in the GTAP model for the construction of LCI data. Wheat consumption in different countries result in different land use consequences due to differences in trade patterns, which are governed by transport and trade costs, among other factors.
Recommendations and perspectives The modelling could be improved by incorporating a mechanism simulating

Preamble The present paper is the second in a series of two. Based on the conceptual aspects outlined in the first paper (Kløverpris et al. 2008), this second paper presents a method for LCI modelling of crop-related land use, which is tested and discussed.

Electronic supplementary material The online version of this article (doi:10.1007/s11367-009-0132-2) contains supplementary material, which is available to authorized users.

J. Hedal Kløverpris (✉)
Department of Management Engineering,
Technical University of Denmark,
Build. 424,
2800 Lyngby, Denmark
e-mail: jklp@novozymes.com

K. Baltzer
Faculty of Life Sciences, Institute of Food and Resource Economics, University of Copenhagen,
Rolighedsvej 25,
1958 Frederiksberg C, Denmark

J. Hedal Kløverpris · P. H. Nielsen
Novozymes A/S, Krogshøjvej 36,
2880 Bagsværd, Denmark

legal fertiliser and pesticide restrictions, by better assessment of the amount of land suitable for livestock but not crop production (grazable land), by including irrigation and by a further differentiation of land fertility. Moreover, the method could be expanded to include intensification aspects in the LCI. The method could inspire a new approach to general LCI modelling in LCA and may also be of interest in the debate on the environmental impacts of biofuels.

Keywords Agriculture · Consequential LCA · GTAP (Global Trade Analysis Project) · Indirect land use change · LCI · Marginal production

1 Introduction

The production of crops is dependent on land, which is a constrained resource in several regions of the world. Increased demand for one crop may therefore lead to displacement of another crop, which may be compensated for by production elsewhere. This presents a challenge when assessing land use impacts in life cycle assessment (LCA) because it complicates the identification of the areas ultimately affected by crop consumption (Kløverpris et al. 2008). Schmidt (2008) develops several scenarios for the identification of ultimate land use caused by wheat consumption in Denmark. In one scenario, barley is applied as the crop displaced by Danish wheat (with reference to Weidema 2003), and Canada is identified as the marginal supplier of barley, i.e. the country compensating for the reduced supply of Danish barley. Canada is pointed out because it is predicted to have the largest gross increase in the production of barley up to 2016 (FAPRI 2006). This approach is a major step forward compared to previous land use assessment in LCA, which has only focused on the direct crop supplier (e.g. Nielsen et al. 2003). However, the identification of the marginal supplier suffers from some weaknesses. For instance, one of the main reasons that Canada has the largest increase in barley production is that it already has the fourth largest area of barley harvested in the world (FAOSTAT 2007). If Canada were subdivided for modelling into smaller units without any changes in agricultural production, the country would no longer be identified as the marginal supplier with the procedure applied. As the identification of marginal suppliers should not depend on the size of countries, there is a need for further improvement of the methodology. This should allow for the possibility that more than one crop in one country is affected by changes in crop demand, which is also acknowledged by Schmidt (2008). Furthermore, transport and trade costs should be taken into account (Kløverpris et al. 2008).

The purpose of the present paper is twofold. Firstly, to present, document and discuss a method for establishing life cycle inventories for land use induced by crop consumption and, secondly, to illustrate the use of the method with concrete examples for consumption of wheat in four countries, each with their own distinct characteristics, namely Brazil, China, Denmark and the USA.

1.1 Scope

Agricultural goods are subject to international trade, and consequently, the geographical scope is global. The study focuses on long-term production and land use changes induced by wheat consumption under present market conditions and with present agricultural technology. The methodological scope comprises consequential LCA and neoclassical economic modelling. The purpose of consequential LCA is to assess the actual consequences of a change, in this case the land use consequences of a decision to use crops in the life cycle of a given product or service.

2 Methodology

The methodology applied in the present study is based on that proposed by Kløverpris et al. (2008). The standard version of the economic model Global Trade Analysis Project (GTAP) is modified and used to predict global land use changes caused by increased wheat demand in the four countries considered. The model is linked with a database, which is also modified slightly. The output from the model consists of relative changes in a number of variables, including agricultural production and land use. These are converted into physical units by use of agricultural statistics. The nature types (biomes) affected by agricultural expansion are determined from land cover maps and FAOSTAT data. The modification of the standard GTAP model is described in detail by Baltzer and Kløverpris (2008). Essentials of the GTAP model in the present context and the stepwise conversion procedure from GTAP outputs to quantification of affected biomes are specified below.

2.1 Modification of the standard GTAP model and database

The GTAP model is a general equilibrium model of the global economy focusing on international trade. The model is based on neoclassical economic theory in which prices adjust to create equilibrium between supply and demand of all goods, services and factors of production in the economy. The accompanying database (version 6) characterises the global economy in 2001 as the initial market equilibrium.

Suppose the initial market equilibrium is disturbed by a sudden increase in demand for wheat. To restore equilibrium, the price of wheat increases, thereby lowering demand and inducing farmers to grow more wheat. The increase in wheat supply can be brought about through three different channels (as discussed in Kløverpris et al. 2008): by converting unused land to agriculture to accommodate the expansion in wheat plantings (increasing demand for land); by intensifying cultivation (raising demand for non-land inputs); or by displacing other crops (lowering supply of non-wheat crops). Each of these channels have implications for other markets, be it land markets, markets for agricultural inputs (such as fertilisers) or markets for substitutable crops.

Thus, the initial shock spreads throughout the economy like ripples on a pond. The general equilibrium model is designed to track all these disturbances throughout the whole economy (as opposed to a partial equilibrium model that only looks at one or few markets in isolation). Also, the global scope of GTAP enables us to track the adjustments across borders through the international trade in goods and services, allowing for the possibility that, e.g. increased wheat demand in Denmark leads to expansions in the agricultural area in Brazil.

The results are determined by the interplay between the model itself (documented in Hertel 1997), the database and a set of behavioural parameters (documented in Dimaranan 2006). We use the standard version of these, modified by the features summarised below (and documented in greater details in Baltzer and Kløverpris 2008).

The standard GTAP database (version 6) contains 87 regions, which are aggregated to 22 in the modified version as this is considered adequate in the present context (Table 1). Each region in the standard model has 57 sectors. Those of main interest in terms of land use are the eight crop sectors and the four livestock sectors.[1] The rest is aggregated to three sectors, resulting in a total of 15 (Table 2).

All eight crop sectors (left column in Table 2) as well as two of the livestock sectors (ctl and rmk) need land for production. The two remaining livestock sectors (wol and oap) do not use land because wool mainly comes from sheep already accounted for in the cattle sector (ctl), and animal products not elsewhere classified (oap) typically come from livestock kept at farms, e.g. pigs and poultry.

[1] In the applied version of the GTAP model, forestry does not use land and is included in the manufacturing sector (mnf). This is simply an artefact of the standard GTAP model, and the study could be improved by incorporating a mechanism in the model that allows land to shift between managed forest and agriculture. Meanwhile, this interplay is partly captured outside the model in the present study because modelled agricultural land expansion can take place at the expense of forest, managed or unmanaged. See Section 2.4.

Table 1 Codes (abbreviations) for the 22 GTAP regions in the present study

Code	Region
aus	Australia
xoc	Rest of Oceania
chn	China
xea	Rest of East and South East Asia
jpn	Japan
xsa	Rest of S Asia
ind	India
can	Canada
usa	USA
mex	Mexico
xca	Rest of Central America
per	Peru
bra	Brazil
xla	Rest of South America
dnk	Denmark
xeu15	EU15 except Denmark
eu12	EU12 (new members)
xer	Rest of Europe
xsu	Rest of Former Soviet Union
xme	Middle East and North Africa
xsc	South African Customs Union
xss	Rest of Sub-Saharan Africa

In the standard model, the total amount of land is fixed, and consequently, simulation of agricultural expansion is not possible. Land supply curves (van Meijl et al. 2006) are therefore incorporated in the GTAP model. Via the following general formula, the land supply curve determines the relationship between land price (P) and the area of land being utilised in the relevant region (the land supply, A_u):[2]

$$P = b/(A_a - A_u) \tag{1}$$

where $b > 0$ is a region-specific coefficient determining the shape of the curve and $A_a > 0$ is the maximum amount of land available in the relevant region.

The general shape of a land supply curve is shown in Fig. 1. At lower degrees of land utilisation in a given region, the land price will be relatively unaffected by changes in land use (the flat part of the curve). At high degrees of land utilisation, the land price will be very sensitive to changes in land use (the steep part of the

[2] Baltzer and Kløverpris (2008) use standard GTAP notation: PM for land price (P), QO for land supply (A_u) and a for the maximum amount of land available (A_a), in accordance with van Meijl et al. (2006).

Table 2 Codes (abbreviations) for the 15 GTAP sectors in the present study

Code	Crop sectors	Code	Other sectors
pdr	Paddy rice	ctl	Bovine cattle, sheep and goats, horses
wht	Wheat	oap	Animal products nec
gro	Cereal grains nec	rmk	Raw milk
v_f	Vegetables, fruit, nuts	wol	Wool
osd	Oil seeds	food	Food processing
c_b	Sugar cane, sugar beet	mnf	Manufacturing
pfb	Plant-based fibres	svc	Services
ocr	Crops nec		

nec not elsewhere classified

curve). Consequently, agricultural expansion is less likely in regions with a high degree of land utilisation.

To better account for differences in land quality, the single land type used in the standard GTAP model is replaced by two land types in the modified version: *cultivable land* with potential for rain fed cropland and pastures and *grazable land* with potential for rain fed pastures only. The eight crop sectors (see Table 2) can only use cultivable land, whereas the land-dependent livestock sectors (ctl and rmk) can use both cultivable and grazable land.

Land supply curves for each land type in each region are implemented in the modified version of the GTAP model. The area of cultivable land available for agriculture (A_a in Eq. 1 for cultivable land) is estimated for each region by a general procedure subtracting steep areas, protected areas and human settlements from the total area of cultivable land estimated by Ramankutty et al. (2002) on the basis of climate and soil constraints. The area of grazable land available for agriculture (A_a in Eq. 1 for grazable land) is estimated for each region by a general procedure subtracting steep and protected areas, human settlements, deserts and cultivable land from the total land area (Fig. 2) implicitly assuming that arid, semi-arid and dry sub-humid areas can be used as pastures. The areas of cultivable land and grazable land utilised in each region (A_u in Eq. 1) are determined by overlaying a global map of cultivable land (Ramankutty et al. 2002) and a global map of cropland and pastures (Ramankutty et al. 2007). Coefficient b (see Eq. 1) is calculated via the following formula (for both land types):

$$b = V_u \times (1 - u)/u \qquad (2)$$

where V_u is the monetary value of land utilised in the relevant region (available in the GTAP database, Dimaranan 2006) and u is the regional utilisation of the relevant land type defined as A_u/A_a.

The so-called Armington elasticities (see Kløverpris et al. 2008) in the standard GTAP database are doubled. Besides representing the heterogeneity of products from the same sectors in different regions, the Armington elasticities capture a number of factors causing inertia in international trade patterns. Much evidence suggests that this inertia is stronger in the short term compared to the long term. This can be explained by long-running contracts or high transaction costs preventing buyers from shifting to a cheaper supplier in response to short-term price variations. The more time the market has to adjust, the more freely buyers will choose between domestic and foreign suppliers. Therefore, the Armington elasticities tend to increase with the time perspective (McDaniel and Balistreri 2002). The

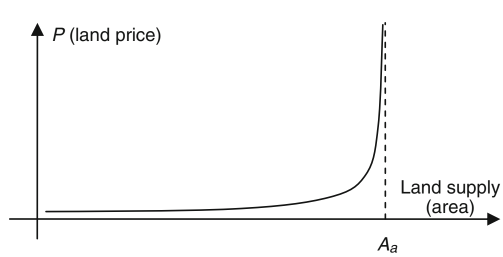


Fig. 1 Land supply curve (adjusted from van Meijl et al. 2006): General relationship between the area of land being utilised (land supply) and the land price. A_a indicates the maximum amount of land available in the region. Equation 1 describes the formula for the curve

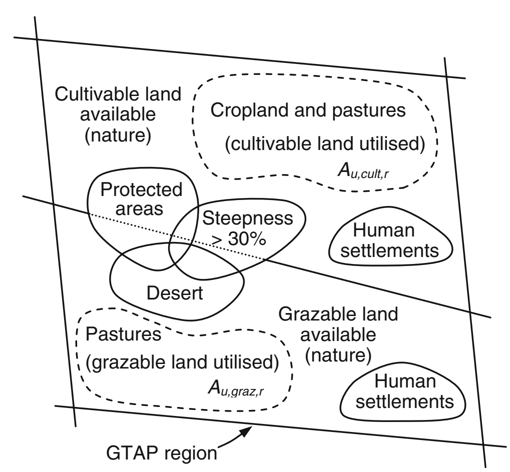


Fig. 2 Conceptual illustration of the regional land uses in the modified GTAP model. Steep and protected areas, human settlements and deserts are not considered available for agricultural production

doubling of the standard Armington elasticities is performed to reflect the long-term perspective usually applied in LCA.

The effect of crop demand on technological development and hence intensification (Kløverpris et al. 2008) is ignored in the core scenarios of this study, but investigated in the sensitivity analyses. The intensification observed in the core scenarios is therefore merely a result of optimised inputs to crop production driven by changes in crop prices. The effects of legal fertiliser and pesticide restrictions (Kløverpris et al. 2008) are not incorporated in the modelling as it has not been possible to establish a global overview of such restrictions.

The GTAP database is modified to better reflect the current world market conditions, e.g. the EU enlargement (from 15 to 27 member states) and China's entry into the WTO (end of 2001).

2.2 Simulation of increased demand for wheat in the GTAP model

The demand for wheat is increased by 500,000 tonnes in the four countries considered. This change is large enough to appear in the output from the GTAP model but small enough to be applicable in LCA, which typically concerns marginal changes compared to the total market (Weidema et al. 1999). The change in demand is constructed in the GTAP model by increasing the household preferences for wheat in the country of interest. The change is implemented in the households because these are end users in society. Establishing increased wheat demand elsewhere (e.g. in the industrial sectors) would create distortions in competitiveness and other effects that are not of interest in the present context. Due to the budget constraint of the households, the increase in wheat demand is balanced by an equivalent and equal decrease (the same relative change) in the household demand for other commodities. This is to make the change in demand as neutral as possible and thereby the results as generally applicable as possible.

2.3 Conversion of the output from the GTAP model

The output from the GTAP model expresses (among other things) the *relative* (percentage) changes in land use and crop production caused by the simulated increase in wheat demand. In order to convert the GTAP output to tonnes of agricultural production and area of agricultural land, it is combined with agricultural statistics (obtained from FAOSTAT 2007 and the overlay described in Section 2.1) in a set of equations, which are available in Electronic supplementary materials (ESM).

Although the expansion of the agricultural area is the main focus of this study, the underlying changes in crop production are also examined to see how they comply with the conceptual analysis presented in the first paper of this series. Thus, Eqs. 3–7 in ESM decomposes the total change in crop production into a part created by land expansion and another part derived from intensification. The crop sectors' change in production from a change in area is estimated (Eq. 6 in ESM) based on the initial distribution of cultivable land (Eq. 3 in ESM), the predicted changes in crop sector land use (Eq. 4 in ESM) and the initial crop yields (Eq. 5 in ESM). The crop sectors' change in production from a change in intensity is residually estimated by subtracting the area-related change in production from the total change in production (Eq. 7 in ESM).

Changes in crop yields are estimated based on production changes from intensification and the new land areas in the crop sectors (Eq. 8 in ESM), whilst the net expansion on cultivable land (both from cropland and pastures) is estimated based on output from the GTAP model (Eq. 9 in ESM).

For the country in which the wheat demand is increased (the scenario country), increased wheat production from change in area is further decomposed into expansion of agricultural area (Eq. 10 in ESM) and displacement of, respectively, other crops (Eq. 11 in ESM) and livestock (Eq. 12 in ESM). This breakdown is only possible for the regions in which the wheat sector is the only sector gaining land from other sectors and nature. This is the case for the scenario country in all scenarios and also for Canada in the US scenarios (due to Canada's close trade relations to the USA).

The net expansion on grazable land (from changes in pasture areas) is estimated from the initial grazable land use (overlay data) and GTAP output (Eq. 13 in ESM), whilst production changes in the livestock sectors are estimated from GTAP output and FAOSTAT production data (Eq. 14 in ESM).

2.4 Biomes affected by net expansion

After quantification of the net expansion caused by wheat consumption, the biomes expected to be affected are identified. Biomes are defined by potential natural vegetation, i.e. the "vegetation that would most likely exist in the absence of human activities" (Ramankutty and Foley 1999).

The net expansion predicted by the GTAP model is divided into two types. In a region with an increasing agricultural area, the predicted expansion is interpreted as transformation of an area that would otherwise have been transformed one season later (accelerated transformation). In a region with a decreasing agricultural area, the predicted expansion is interpreted as utilisation of agricultural land that would otherwise have been released one season earlier (delayed relaxation). In this study, one constant land quality (x) is assumed for agricultural land (cropland and pastures).

On the assumption that land released from agriculture returns to its original, natural quality (y) at a constant speed, the framework for land use life cycle impact assessment (LCIA) developed by Milá i Canals et al. (2007) shows that the impact of the two types of expansion is the same as long as the occupation period (from t_1 to t_2) is the same (Fig. 3). As all data in the GTAP model is given per year, the occupation period for all areas transformed is the same. If two areas of the same biome are affected by different types of expansion, these areas are therefore added up in the present paper. The background data, however, allow for a disaggregation of the two types of expansion. Note that because either type of expansion occurs on areas already about to change, the long-known problem of allocating initial transformation impacts to subsequent land use activities (see, e.g. Lindeijer et al. 2002) is eliminated.

To determine the biomes affected by expansion in a GTAP region, the likely geographical location of expansion *within* the region is first identified. This is done by first analysing the trend in utilisation of the two land types, cultivable and grazable land. The trend analysis is based on data for cropland and pasture areas (FAOSTAT 2007) and data on the relative land type utilisation.[3] Thereafter, the trends in croplands and pastures are used as indicators of where in the region the expansion predicted by the GTAP model occurs. Data on these trends consists of agricultural statistics (FAOSTAT 2007) and cropland maps from 1970 and 1990 (Ramankutty and Foley 1999). Finally, the potential natural vegetation (biome) of the areas affected by expansion is determined by identifying these areas on a digital biome map with a global overview of 15 potential natural vegetation types (Ramankutty and Foley 1999). This full procedure is described by Kløverpris (2008).

3 Results

The studied increase in household wheat consumption leads to an increase in the global production of wheat distributed among the marginal wheat suppliers, i.e. those responding to a change in demand. The changes in wheat production affect the production of other crops and livestock due to the displacement–replacement mechanisms (Kløverpris et al. 2008). All the changes in agricultural production result in net expansion of the global agricultural area, which affects natural areas in terms of biomes. This section presents changes in agricultural production as well as the resulting land use effects. The results are explained and interpreted in terms of the assumptions of the GTAP model and the economic theory behind it.

[3] Determined from the overlay mentioned in Section 2.1.

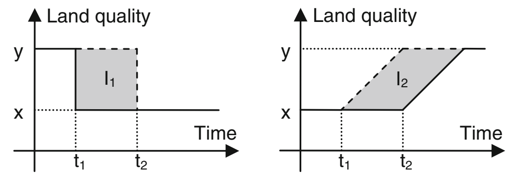


Fig. 3 Impact of accelerated transformation (I_1) and delayed relaxation (I_2). The *full line* indicates land quality at the studied increase in crop demand, and the *dashed line* indicates the development if the current trend in demand is unaffected (dynamic reference situation). I_1 is equal to I_2

A key purpose of LCA is to determine the environmental consequences of product consumption. All results are therefore presented per tonne of increased wheat consumption in the households of the scenario countries. Note that the increase in consumption is slightly lower (by less than 0.2%) than the demand shock (500,000 tonnes). This is the net effect of two opposing forces, an increase by the demand shock itself (500,000 tonnes) and a small decline due to a higher wheat price generated by the demand shock (a negative relationship between demand and price is a standard assumption in economics).

3.1 Localisation of affected wheat suppliers and characterisation of increased wheat production

Figure 4 shows the estimated changes in wheat production induced by wheat consumption. The results include the wheat seeds consumed by the wheat sector itself. That is why the total increase in wheat production in the Chinese scenario exceeds 1 tonne. In the Brazilian, Chinese, Danish and US scenario, the net increase in total wheat production (subtracting the wheat sectors' own consumption) is, respectively, 84%, 98%, 91%, and 93% of the increased household wheat consumption in the scenario country (calculated based on background data not available in this paper). This shows that when wheat is consumed, most of it is provided by increased production but some of it (2–16%) is taken from applications in other sectors because the supply of wheat is not perfectly elastic.

The results in Fig. 4 reflect existing trade patterns as well as the prevailing constraints on land availability. Increased wheat consumption in China and Brazil is almost entirely sourced from domestic production. Prior to the change in demand, imports account for, respectively, 1% and 3% of the two countries' household wheat consumption. An increase in wheat demand is therefore met primarily by an increase in domestic wheat production. In contrast, 40% of US and 23% of Danish household wheat consumption is covered by imports (prior to the change in demand), and substantial parts of the increased demand for wheat is consequently met by growth in wheat production outside these countries.

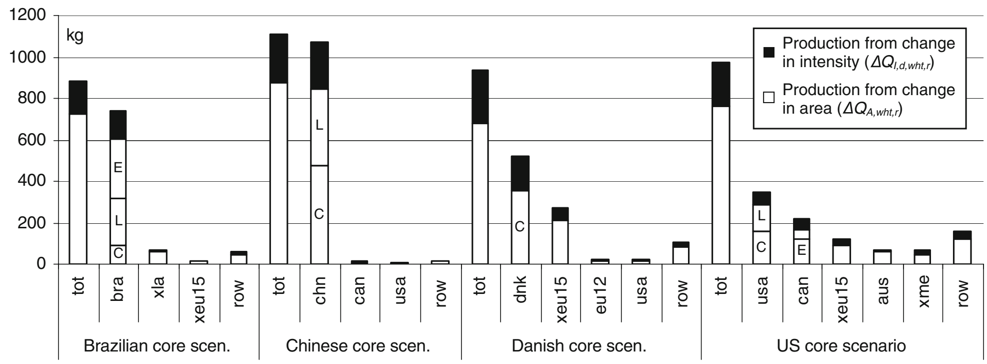


Fig. 4 Wheat production caused by consumption of one (additional) tonne of wheat in the four core scenarios. For the scenario countries, the change in wheat area is split into expansion (*E*) and displacement of other crops (*C*) and livestock (*L*). For Canada in the US scenario, production caused by expansion is also indicated. The regions with the lowest increase in wheat production are presented together as '*row*' (rest of the world), and '*tot*' stands for total

Similarly, which countries respond to the increasing demand for wheat imports is largely determined by existing trade patterns. For instance, higher household wheat consumption in the USA results in a significant increase in Canadian wheat production due to the traditional close trade relations between the two countries. This trade pattern in turn reflects low costs of transportation and the relatively small barriers to trade within the North American free trade area.

Interestingly, the availability of unused agricultural land has little influence on *where* the extra wheat is produced. The reason is that the production costs related to land typically constitutes 20% or far less of the total production costs of crops. Therefore, a change in land prices has a minor effect on market prices (which depend on production costs). On the other hand, land availability determines *how* the extra wheat is produced in the regions responding to the change in demand. In countries such as Brazil and Canada with large areas of unutilised cultivable land, expansion accounts for a large share of the increased crop production. For instance, one third of Brazil's increase in wheat production derives from expansion. Denmark and China utilise all of their cultivable land, and their increase in wheat production consequently derives from displacement and intensification. The reason why wheat production does not displace livestock in Denmark is that pastures are insignificant on Danish cultivable land.

In the Brazilian core scenario, the intensified wheat production in Brazil corresponds to an increase in wheat yields of 1.8% (37 kg/ha). Compared to the rather low initial wheat yields calculated for Brazil (roughly 2 tonnes/ha or less than a third of Danish wheat yields), the calculated yield increase per hectare seems realistic. In the Chinese and the US core scenarios, the intensified wheat production in the scenario country corresponds to an increase in wheat yields of, respectively, 0.12% (5 kg/ha) and 0.06% (1 kg/ha), which is also considered realistic. In the Danish scenario, however, the number is 1.7% or 120 kg/ha, which is quite high considering the strict regulations on pesticides and fertilisers in Denmark and the fact that Denmark already has some of the world's highest wheat yields. If the restrictions mentioned had been included in the modelling, the intensification in Denmark (and probably the rest of EU) would most likely have been somewhat lower.

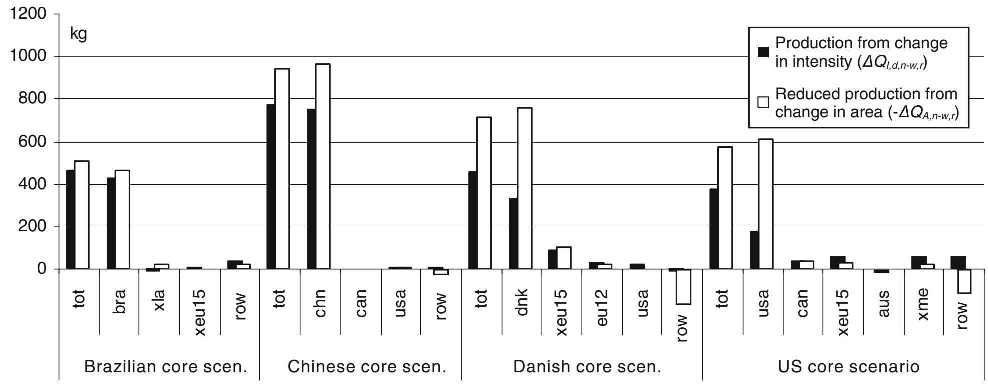
3.2 Production changes for non-wheat crops and livestock

The increased production of wheat leads to changes (mainly reductions) in the areas planted with other crops. However, this is partly compensated for by intensification. The changes in production of non-wheat crops (the remaining seven crop sectors) are added up to get an indication of the ratio between reduced production due to change in area and the production from change in intensity (Fig. 5).

For the scenario countries, there is a direct connection between the wheat production obtained by displacement of other crops (see Fig. 4) and the reduced production of other crops due to change in area (see Fig. 5). The reason for the large reduction in non-wheat crop production in the Brazilian core scenario (compared to the relatively small increase in Brazilian wheat production caused by crop displacement) is that most of the crop sectors in Brazil have a significantly higher yield per hectare than the wheat sector.

Figure 5 displays a large variation in the degree to which displacement of non-wheat crops is compensated for by intensification of production. In Brazil and China, the intensification of non-wheat crop production almost set off the reduction in production caused by displacement with wheat (with yields of non-wheat crops increasing by roughly 0.04% and 0.035%, respectively). In contrast, intensification generates less than half the quantity of displaced crops in Denmark and the USA (where the yields of non-wheat crops rise by roughly 0.6% and 0.01%, respectively). This is not

Fig. 5 Production of non-wheat crops (*n-w*) caused by consumption of one (additional) tonne of wheat in the scenario countries. Note that the *white bars* indicate *reduced* production so the net change in production is the difference between the *black bars* and the *white bars*. The regions not mentioned explicitly are presented together as '*row*' (rest of the world), and '*tot*' stands for total



explained by differences in ability to intensify production but rather by the existing trade patterns. The economies seek to compensate for reduced cultivation of non-wheat crops due to displacement in the cheapest way possible. In Denmark and particularly the USA, international trade costs are relatively low, and it is cheaper to reduce exports and/or raise imports of crops than to intensify production. In a sense, these countries succeed in 'exporting' much of the displacement, thus sharing the burden of intensifying production over a wider area. This also accounts for the 'negative displacement' observed in some of the columns for the rest of the world (row) in Fig. 5; the rising demand from the scenario countries induces an expansion in the area for cultivation of non-wheat crops. In contrast, Brazil and China do not trade much in agricultural commodities (although they do have considerable international trade in processed food), and there are fewer opportunities to obtain displaced production through trade. Hence, they find it less costly to intensify production. Note that at the global scale, the degree of compensation is still lower in the Danish and US scenarios, implying a greater reduction in the final consumption of other crops compared to the Brazilian and Chinese scenarios. Again, the costs of adjustment, this time in terms of reduced consumption, are spread over a wider area, reducing the need for intensification.

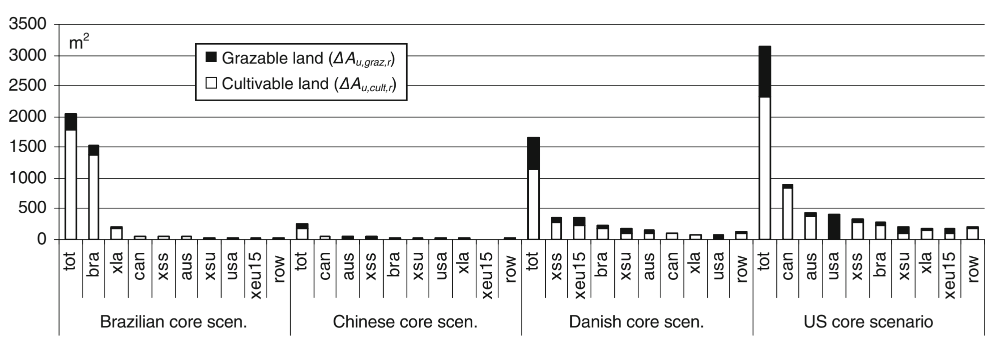
Despite the displacement of livestock (see Fig. 4), the global production in the two affected sectors (ctl and rmk) does not change significantly (calculation based on Eq. 14 in ESM). The reason is that the decrease in cultivable land in the livestock sectors is partly set off by expansion on grazable land (see Fig. 6) and partly by substitution with capital and labour. As these two production factors are not normally accounted for in LCA, livestock production has been omitted in the remaining part of the paper except for its influence on net expansion.

3.3 Net expansion induced by wheat consumption

The changes in area in the different crop and livestock sectors add up to a net change in the use of cultivable and grazable land. Figure 6 shows that increased wheat consumption in Denmark and the USA leads to considerable expansion elsewhere in the world, whereas increased consumption in Brazil primarily leads to domestic expansion. Increased wheat demand in China primarily leads to intensification and expansion effects are limited. More than 90% of the net expansion takes place in the same eight regions and more than two thirds (and up to 87%) of the total net expansion occurs on cultivable land.

The large differences in total net expansion observed between the four core scenarios are caused by several factors. In the case of China (which has no expansion potential), intensification compensates for a large fraction of the displacement of non-wheat crops (see Fig. 5). This means that little production (and thereby expansion) is necessary outside the country. The differences in global net expansion between the remaining three scenarios have to do

Fig. 6 Net expansion caused by consumption of one (additional) tonne of wheat in the scenario countries. The regions with the lowest net expansion are presented together as '*row*' (rest of the world), and '*tot*' stands for total



with several factors including yields per hectare in the regions where expansion takes place. The lower the yields, the more land is necessary for the increase in production caused by an overall change in the agricultural area. Of course, expansion is also influenced by the level of intensification in the main regions affected.

The expansion on grazable land (13–31% of global net expansion) takes place because of livestock displacement on cultivable land. To compensate for this loss of land in the livestock sectors, grazable land is taken into production. Thereby, wheat consumption pushes livestock from one land type to another.

The reason why 75% of the expansion in the Brazilian scenario takes place in Brazil itself is the country's large expansion potential previously mentioned. Ten per cent of the expansion takes place in the rest of South America (excluding Peru) due to easy market access and availability of land (respectively, 82% and 84% utilisation of cultivable and grazable land).

The expansion in the Danish, Chinese and US scenario is distributed over several countries. This shows how the displacement–replacement mechanisms channel the land use effects in terms of expansion through the agricultural system. The reason why the distribution of expansion between the affected countries is not the same in each scenario has to do with several factors, e.g. trade barriers, transport costs and the Armington elasticities. All expansion in the USA occurs on grazable land because of the full utilisation of cultivable land.

3.4 Land use LCI for wheat consumption

By use of the method summarised in Section 2.4, the results in Fig. 6 are converted to a land use life cycle inventory (LCI), which lists the biomes expected to be affected by the expansion induced by consumption of 1 tonne of wheat (Table 3). In the Brazilian scenario, almost 75% of the expansion takes place on tropical evergreen forest mainly in Brazil itself (and a small fraction in xla and xss). In the Chinese scenario, savanna and boreal deciduous forest each make up roughly 20% of the biomes affected, whilst open shrubland and tropical evergreen forest accounts for roughly 15% each. Interestingly, this distribution is more or less the same in the US scenario except that boreal deciduous forest accounts for 27% of the biomes affected. This difference is explained by Canada's large share of global expansion in the US scenario (see Fig. 6). Besides that, the regions contributing to global net expansion in the US and the Chinese scenarios appear in the same descending order if the USA is ignored (see Fig. 6). This also explains the similarities in distribution of biomes affected in the two scenarios. In the Danish scenario, savanna and tropical evergreen forest dominates the biomes affected by, respectively, 18% and 21%, whilst dense shrubland account for 15%. The tropical forest is mainly located in Sub-Saharan Africa and Brazil (more or less equal shares) and the savanna is mainly located in Sub-Saharan Africa and Australia. The figures in Table 3 can be used as the basis for a life cycle impact assessment of the land transformation and subsequent occupation induced by wheat consumption (see Fig. 3).

4 Sensitivity analyses

Some aspects of the economic modelling could have been performed differently. This section investigates the sensitivity to changes in the modelling considered relevant for the methodological exploration of life cycle inventory modelling of land use.

4.1 Linearity check

The global economic system is not linear. In the double demand (DD) scenarios, it is therefore tested how it will affect the results when the change in wheat demand is one million tonnes instead of 500,000. This only has a minor influence on global production of wheat and other crops (given per tonne of household wheat consumption in the scenario countries). The largest differences are observed in the Brazilian DD scenario where the global net expansion is 3% lower compared to the core scenario. The results of the core scenarios can therefore be considered valid for LCAs addressing changes in wheat consumption below one million tonnes per year. Figure 7 shows how the results for net expansion in the Danish DD scenario are practically unchanged compared to the core scenario (see Fig. 6).

Table 3 Land use LCI for consumption of 1 tonne of wheat in the core scenarios

Biomes (m^2)	Braz.	Chin.	Dan.	US
Savanna	230	53	300	590
Tropical evergreen forest	1,500	44	350	460
Boreal deciduous forest	57	49	97	850
Evergr./deciduous mixed forest	25	14	200	160
Dense shrubland	29	10	260	140
Grassland/steppe	120	24	150	210
Open shrubland	43	38	170	480
Boreal evergreen forest	4	4	10	51
Rest (biomes unknown)	35	24	130	210
Total net expansion	2,000	260	1,700	3,200

Numbers indicate the areas subject to expansion (accelerated transformation or delayed relaxation) including 1 year of agricultural occupation. Biome definitions adopted from Ramankutty and Foley (1999). Inconsistencies occur due to rounding

4.2 Demand driven technological development

Technological development can help farmers to obtain higher crop yields per hectare (intensification) without changing the basic inputs to crop production. To investigate the effects of demand-driven technological development on global net expansion, the technological development (TD) scenarios are constructed. This is done by linking price of cultivable land with the productivity of cultivable land in the GTAP model, so a 2% increase in land price automatically causes a 1% increase in land productivity. More specifically, 100 ha of land with productivity improved by 1% are equivalent to 101 ha of land with unimproved productivity. The magnitude of the relationship between land price and land productivity is arbitrarily chosen as no data are identified to form an empirical basis. The relationship is asymmetric in the sense that a decrease in land price will not lead to a decrease in land productivity. This is to reflect the fact that technological development is not rolled back in case of decreasing demand. The mechanism described is only implemented for the crop sectors.

In the TD scenarios, the total increase in wheat production is only slightly different than in the core scenarios (4% higher in the Danish scenario, less than 1% change in the others), but as expected, intensification accounts for a larger share. This is more pronounced in the Danish and US TD scenarios than in the Brazilian and Chinese TD scenarios. In all the TD scenarios, the displacement of non-wheat crops is significantly higher than in the core scenarios, but this is almost fully compensated for by intensification (99%), except for the Chinese scenario in which the compensation level is 88%. Compared to the core scenarios, the established link between land price and land productivity reduces the net expansion in the TD scenarios, but not with the same share. In the Danish and Chinese TD scenarios, the global net expansion is reduced with roughly 80%, whereas it is, respectively, 57% and 27% in the in the US and Brazilian TD scenarios. Figure 7 shows the results for net expansion in the Danish TD scenario.

4.3 Armington elasticities

As mentioned previously, the Armington elasticities (representing the inertia of global trade patterns) tend to increase with the time perspective. In this sensitivity analysis, the effects of increasing the Armington elasticities applied in the core scenarios are investigated. The elasticities are doubled in the double Armington (DA) scenarios (four times the standard Armington elasticities) and then doubled again in the quadruple Armington (QA) scenarios (eight times the standard values).

Higher Armington elasticities imply that consumers are more inclined to substitute cheaper imports for more expensive domestic production. In other words, with less inertia in the global trade, the international trade patterns play a less dominant role (compared to, say, the potential for expansion in the agricultural area) in explaining the results. Imports of wheat in the scenario countries increase more, causing their own increase in wheat production to go down compared to the core scenarios. The domestic production increase in the scenario countries is 20% and 40% lower in all the DA and QA scenarios, respectively, except for the Chinese DA and QA scenarios in which the increase is, respectively, 4% and 10% lower.

Compared to the core scenarios, the overall increase in wheat production is lower in the DA and QA scenarios, but more wheat is produced outside the scenario countries. The effect on global net expansion depends on how the scenario country and its suppliers increase wheat production. When the increase in wheat production partially moves out of Brazil due to the higher Armington elasticities, the global net expansion is lower than in the core scenario (DA, −13%; QA, −24%). This is because expansion plays a significant role in Brazil's domestic increase in wheat production (see Fig. 4). On the other hand, increasing Armington elasticities lead to increased global net expansion from wheat consumption in China (DA, 55%; QA, 124%) and Denmark (DA, 30%; QA, 50%). This is because wheat production is partially moved to regions with expansion potential. For US wheat consumption, the changes in Armington elasticities do not change the global net expansion significantly, although there is also some redistribution of expansion between regions. Figure 7 shows the results for net expansion in the Danish DA and QA scenarios. In summary, the results of the modelling are clearly sensitive to modifications of the Armington elasticities. Interestingly, the fraction of increased global wheat production achieved through intensification is more or less unaffected by the Armington modification.

5 Uncertainties

This section provides a qualitative assessment of the most important sources of uncertainty influencing the results of the study.

The land supply curves introduced in the modified GTAP model are based on data and assumptions concerning land availability and land utilisation. The data on areas not available for agriculture (steep and protected areas, human settlements and deserts) are considered to be of good quality, but lack of information about possible overlaps between these areas creates inherent uncertainties in the general procedures applied to calculate the areas of

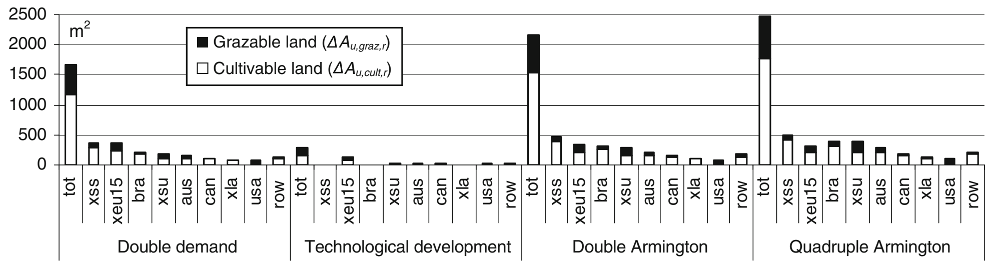


Fig. 7 Sensitivity analysis of the net expansion caused by consumption of one (additional) tonne of wheat in Denmark. The regions with the lowest net expansion are presented together as '*row*' (rest of the world), and '*tot*' stands for total

cultivable and grazable land available for agriculture (for details, see Baltzer and Kløverpris 2008). Furthermore, the assumption that arid, semi-arid and dry sub-humid areas can be used as pastures (see Section 2.1) may cause an overestimation of expansion on grazable land (see Fig. 6). As this only constitutes a minor part of global net expansion, the uncertainty introduced is judged to be low.

To ensure consistency in the modelling, data from around 2001 have been used to the extent possible. The GTAP database corresponds to 2001; data on cropland and pasture areas are from around 2000 (see Section 2.1), and data on crop production and area harvested are from 2001 (see ESM). The uncertainty introduced by assuming results to be valid for current conditions is considered to be low especially because of the update of the GTAP database (see Section 2.1).

The calculation of the areas occupied by the different crop sectors (Eq. 3 in ESM) is based on yearly areas harvested, which may be larger than actual cropland areas because some crops are harvested more than once a year (high cropping intensity). However, crop sectors in the same region are likely to have similar cropping intensities because of similar climatic conditions. This reduces the uncertainty introduced in the procedure described.

The areas calculated in Eq. 3 in ESM are combined with crop production data in Eq. 5 (see ESM) to calculate yearly crop yields per hectare. This combination of datasets deriving from two different sources also introduces some uncertainty, which is difficult to assess as no comparable global dataset is identified. However, the uncertainties relating to Eqs. 3 and 5 in ESM only affect the *distribution* between crop production from, respectively, change in area and intensity. The total crop production in a sector is unaffected as it is calculated from the GTAP output and the initial crop production (appears implicitly from Eq. 7 in ESM).

The identification of biomes affected by expansion is partly based on a qualitative assessment. However, the conclusions on the trends in utilisation of cultivable and grazable land are fairly unambiguous for the eight regions studied, and the certainty of this part is generally considered good. The subsequent identification of the areas affected within the regions (and thereby the biomes affected by expansion) is less certain (Kløverpris 2009a). Consequently, the result should only be considered a reasonable estimate of the biomes most likely to be affected by agricultural expansion.

6 Discussion

The method presented in the present paper makes it possible to produce even more detailed results than those presented in Section 3. Furthermore, the method contains elements with general implications for LCA. These aspects are discussed below.

6.1 Possibilities for a more detailed and disaggregated land use LCI

Some simplifying assumptions regarding land quality are used in this study (see Section 2.4). Only net expansion of the agricultural area is considered, and thereby the land use LCI (see Table 3) does not distinguish between transformation from nature to cropland and transformation from nature to pastures (although the two agricultural land uses may result in different land qualities). If such a distinction were made, it would be necessary to list the land converted from pastures to cropland (displacement of livestock) in the land use LCI. The background data of the study actually offer this possibility (see Kløverpris 2009b). In fact, it would be possible to include all shifts in land use between the eight crop sectors, the two land-dependent livestock sectors and nature in all of the 22 GTAP regions. Furthermore, it would be possible to distinguish between the two types of net expansion (accelerated transformation and delayed relaxation). This level of detail is considered exaggerated in the present paper, but is nonetheless obtainable with the method described.

6.2 The influence of existing trade patterns

It may seem strange that the existing trade patterns have such a large influence on the suppliers responding to increased wheat demand whilst the availability of unused land only plays a minor role. The reason is that trade patterns are governed by prices of different suppliers (taking into account transport, tariffs and other trade barriers). If Denmark satisfies most of its current wheat demand from domestic production and imports from the rest of the EU, it must be because they are the cheapest suppliers under the current market conditions. As mentioned in Section 3, the price of land only has little influence on the price of crops. Therefore, the change in demand for wheat will not lead to a significant change in crop prices, and trade patterns are only affected marginally. Fair to say, there is one more significant aspect explaining why existing trade patterns have such a large influence on the results, namely the Armington elasticities.

6.3 Armington elasticities and time perspectives in LCA

The inertia of global trade patterns represented by the Armington elasticities is normally not considered in LCA. However, this aspect should be acknowledged whilst still respecting the long-term perspective applied in LCA. That is why Armington elasticities twice as high as the standard values are applied in the core scenarios. It may be argued that a further enlargement of the Armington elasticities would be more in line with the LCA methodology, but considering the land use LCIA framework mentioned in Section 2.4 in which a change in land quality is compared to a reference situation (business as usual), it does not make sense to apply a time perspective which is too long. The reason is that land use change induced by crop consumption occurs within a foreseeable future, i.e. when the market reacts. This reaction takes place under the given constraints represented by the Armington elasticities. Thereby, the elasticities are legitimate in an LCI analysis. If economic modelling gains a footing in LCA, it would be desirable to obtain consensus on the appropriate size of the Armington elasticities.

6.4 LCI data based on consumption instead of production

Most LCI data currently available represent *production* of a certain amount of product. The land use LCI presented in Table 3 is different as it represents *consumption* of a certain amount of product. As described in Section 3.1, increased household consumption of 1 tonne of wheat causes the net production of wheat to increase by 840–980 kg whilst the total production of other crops decreases by 41–260 kg. All changes in agricultural production are triggered by wheat consumption, and it is the land use consequences of this consumption, which are reflected in Table 3. The reason why the net production of wheat does not increase with 1 tonne (equivalent to the increase in household consumption) is that the wheat sector has to compete with other sectors for resources in terms of intermediate inputs and primary production factors being capital, labour and land. The amount of capital and labour at a given moment is fixed so land is the only primary production factor for which the amount can be increased. As more land is being utilised, the land price increases (see Fig. 2). The marginal costs of crop production thereby increase, which explains why the supply of crops is not perfectly elastic. In order to determine the environmental impacts of crop consumption, this premise of the market should be taken into account as it is done in this study.

6.5 Accounting for the decrease in demand for non-wheat products

The competition for resources is not the only reason for the decrease in production of non-wheat crops. As described in Section 2.2, the increased demand for wheat is simulated at the expense of demand for other products due to the budget constraint of the households. Because this decrease in demand is distributed over many other products, the influence on the non-wheat crops is relatively small. Nonetheless, it affects the results to some degree. This situation is not uncommon in LCA where one alternative is typically studied in comparison to another. In other words, LCA is applied to study the consequences of increasing the demand for one solution and simultaneously decreasing the demand for another solution. The problem is that when constructing inventory data, only one side of the story is considered, namely the increase in demand. Not until the full LCA is performed is the decrease in demand addressed. However, if life cycle inventory data were established by use of a general economic equilibrium model and the decrease in demand were always modelled consistently (e.g. by the procedure described in Section 2.2), the decrease in demand implicitly reflected in the obtained LCI data would tend to be cancelled out once a full LCA were performed. This opens up new perspectives and possibilities for the future construction of life cycle inventories.

7 Conclusions

The analysis in the present paper shows that economic modelling in combination with geographical data and agricultural statistics can indeed help to overcome some of the obstacles of identifying ultimate or marginal land use changes when studying crop consumption in LCA. It is shown that the displacement–replacement mechanisms of agricultural land use can be handled in a global context, and the relevance of where the demand is increased can be taken into account (the geographical dependency). Furthermore, the methodology eliminates the long-known problem of allocating initial transformation impacts to subsequent land use activities, and it provides an estimation of the ratio between production achieved through change in, respectively, intensity and area. The linearity check in the sensitivity analyses shows that the results are valid for changes in wheat consumption within an amount of one million tonnes per year, which means that the results are applicable to a wide range of LCAs. Furthermore, the study presents a proposal on how to model the influence of demand on technological development, but the exact relationship is not determined. The results are sensitive to changes in the Armington elasticities in the GTAP model representing the inertia of global trade patterns. In this study, it is considered reasonable to double the standard Armington elasticities.

In the core scenarios, it is estimated that the consumption of 1 tonne of wheat in, respectively, Brazil, China, Denmark and the USA leads to a global increase in wheat production between 880 kg (Brazil) and 1,100 kg (China). The net increase in wheat production (excluding the wheat used for seeds) is between 840 kg (Brazil) and 980 kg (China). Brazil and China account for most of the global increase in wheat production themselves (84% and 97%, respectively), whilst Denmark and the USA account for roughly half and one third, respectively.

In the core scenarios, intensification accounts for approximately 20% of the global increase in wheat production, except for the Danish scenario in which it is almost 30%. This may be overestimated as restrictions on fertilisers in Denmark (and the EU) are not taken into account.

In Brazil, roughly half of the increase in wheat production from change in wheat area comes from expansion. The rest comes from displacement of other crops and livestock. In China and the USA, the increase in wheat production from change in the wheat area comes from displacement of other crops and livestock, and in Denmark, it only comes from displacement of other crops (as livestock is insignificant on cultivable land). Despite livestock displacement, there is no significant change in the overall livestock production partly because production is moved to another land type (grazable land) and partly due to substitution of land with capital and labour.

In Brazil and China, the displacement of other crops is almost fully compensated for by intensification (92% and 78%, respectively), whilst Denmark and the USA mainly compensate the displacement of other crops by increased imports (but also some intensification).

Consumption of wheat in China and the USA is expected to mainly affect savanna, boreal deciduous forest, open shrubland and tropical evergreen forest. However, the global net expansion induced by consumption of 1 tonne of wheat in China is estimated at 260 m^2, whereas it is roughly 3,200 m^2 for 1 tonne of wheat consumed in the USA. For Brazil, the net expansion per tonne of wheat consumed is approximately 2,000 m^2 presumed to mainly affect tropical evergreen forest in the country itself, and for Denmark, it is roughly 1,700 m^2 presumed to mainly affect savanna, tropical evergreen forest and dense shrubland.

8 Recommendations and perspectives

As mentioned previously, integration of mechanisms simulating fertiliser and pesticide restrictions in the GTAP model would raise the quality of the results. The assessment of the amount of grazable land can also be improved. Taking irrigation into account would also improve the modelling as well as a further differentiation between different levels of land fertility. Finally, the method could be expanded to include not just land use (transformation and occupation) but also the intensification aspects and the implications for life cycle inventory modelling. This has briefly been discussed in the first paper of this series (Kløverpris et al. 2008).

The method applied in this study to identify land use induced by crop consumption could inspire a new way of doing LCA, taking its point of departure in consumption and not production. If this is based on economic modelling, it is recommended to seek consensus on how to handle the Armington issue.

The method may also inspire the debate about biofuels and the natural areas affected by their production. However, it is important to keep in mind that the examples presented in this study consider marginal changes in crop consumption compared to the total market, whereas the production of biofuels typically concern larger changes. Furthermore, it would be necessary to construct a much more specific demand change in the case of biofuels, taking into account the interaction with fossil fuels.

Acknowledgements The authors are grateful to Navin Ramankutty, McGill University, Montreal, Canada for valuable assistance with the overlay of the maps described in Section 2.1.

References

Baltzer K, Kløverpris J (2008): Improving the land use specification in the GTAP model. Institute of Food and Resource Economics, University of Copenhagen, Working Paper no. 2/2008. Available from www.foi.dk

Dimaranan BV (ed) (2006): Global trade, assistance, and production: the GTAP 6 data base. Center for Global Trade Analysis, Purdue University

FAOSTAT (2007) United Nations Food and Agricultural Organisation. http://faostat.fao.org

FAPRI (2006) U.S. and world agricultural outlook. Food and Agricultural Policy Research Institute, Iowa

Hertel TW (1997) Global trade analysis: modeling and applications. Cambridge University Press, Cambridge

Kløverpris J (2009a) Identification of biomes affected by marginal expansion of agricultural land use induced by increased crop consumption. J Clean Prod 14:463–470

Kløverpris J (2009b) Consequential life cycle inventory modelling of land use induced by crop consumption. PhD dissertation, Department of Management Engineering, Technical University of Denmark

Kløverpris J, Wenzel H, Nielsen PH (2008) Life cycle inventory modelling of land use induced by crop consumption. Part 1: conceptual analysis and methodological proposal. Int J LCA 13:13–21

Lindeijer E, Müller-Wenk R, Steen B (2002) Impact assessment of resources and land use, chapter 2. In: Udo de Haes HA, Finnveden G, Goedkoop M, Hauschild M, Hertwich EG, Hofstetter P, Jolliet O, Klöpffer W, Krewitt W, Lindeijer E, Müller-Wenk R, Olsen SI, Pennington DW, Potting J, Steen B (eds) Life-cycle impact assessment: striving towards best practice. SETAC, Pensacola

McDaniel A, Balistreri EJ (2002) A review of Armington trade substitution elasticities. US International Trade Commission, Washington

Mila i Canals L, Bauer C, Depestele J, Dubrscseuil A, Knuchel RF, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007) Key elements in a framework for land use impact assessment within LCA. Int J LCA 12:5–15

Nielsen PH, Nielsen AM, Weidema BP, Dalgaard R, Halberg N (2003) LCA food data base. www.lcafood.dk

Ramankutty N, Foley JA (1999) Estimating historical changes in global land cover: croplands from 1700 to 1992. Glob Biogeochem Cycles 13:997–1027

Ramankutty N, Foley JA, Norman J, McSweeney K (2002) The global distribution of cultivable lands: current patterns and sensitivity to climate change. Glob Ecol Biogeogr 11:377–392

Ramankutty N, Evan AT, Monfreda C, Foley JA (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Glob Biogeochem Cycles 22:GB1003.1–GB1003.19. doi:10.1029/2007GB002952

Schmidt J (2008) System delimitation in agricultural consequential LCA—outline of methodology and illustrative case study of wheat in Denmark. Int J LCA 13:350–364

van Meijl H, van Rheenen T, Tabeau A, Eickhout B (2006) The impact of different policy environments on agricultural land use in Europe. Agric, Ecosyst Environ 114:21–38

Weidema BP (2003) Market information in life cycle assessment. Danish Environmental Protection Agency, Danish Ministry of Environment. Environmental Project no. 863

Weidema BP, Frees N, Nielsen AM (1999) Marginal production technologies for life cycle inventories. Int J LCA 4:48–56

Appendix

This appendix contains the equations applied to convert the output from the GTAP Model to mass of production and area of agricultural land. The term *scenario country* is used to designate the country in which the demand for wheat is changed, and the term *initial* indicates the state before the change in demand. Indices *r* and *c* are used for region and crop sector, respectively.

To calculate the initial area of cultivable land used by a crop sector in a region ($A_{u,cult,c,r}$), it is assumed that the distribution of cropland between crop sectors is equal to the distribution of the area harvested.

$$A_{u,cult,c,r} = H_{c,r} / H_{tot,r} \cdot A_{crop,r} \qquad (3)$$

where

$H_{c,r}$ is the area harvested in 2001

$H_{tot,r}$ is the total area harvested in 2001

$A_{crop,r}$ is the total cropland area

Data on area harvested in the eight crop sectors of the 22 GTAP regions is compiled by manually grouping the data from FAOSTAT (2007) covering more than 200 countries and 146 primary crops.

On the basis of **Eq. 3**, the change in area in a crop sector ($\Delta A_{u,cult,c,r}$) is calculated from

$$\Delta A_{u,cult,c,r} = A_{u,cult,c,r} \cdot q_{lnd,cult,c,r} \qquad (4)$$

where

$q_{lnd,cult,c,r}$ is the relative change in cultivable land being utilised (GTAP output)

The initial annual yield per hectare in a crop sector ($Y_{c,r}$) is calculated from

$$Y_{c,r} = Q_{c,r} / A_{u,cult,c,r} \qquad (5)$$

where

$Q_{c,r}$ is the initial production in crop sector *c*

Production data for the eight crop sectors of the 22 GTAP regions is compiled in the same manner as described for area harvested.

The change in production caused by change in area in a crop sector ($\Delta Q_{A,c,r}$) is calculated from

$$\Delta Q_{A,c,r} = Y_{c,r} \cdot \Delta A_{u,cult,c,r} \qquad (6)$$

The change in production caused by demand driven intensification in a crop sector ($\Delta Q_{I,d,c,r}$) is calculated from

$$\Delta Q_{I,d,c,r} = Q_{c,r} \cdot q_{o,c,r} - \Delta Q_{A,c,r} \qquad (7)$$

where

$q_{o,c,r}$ is the relative change in production in crop sector *c* (GTAP output)

The change in yields in a crop sector ($\Delta Y_{c,r}$) is calculated from

$$\Delta Y_{c,r} = \Delta Q_{I,d,c,r} / (A_{u,cult,c,r} + \Delta A_{u,cult,c,r}) \qquad (8)$$

The net expansion on cultivable land in a region ($\Delta A_{u,cult,r}$) is calculated from

$$\Delta A_{u,cult,r} = A_{u,cult,r} \cdot q_{o,cult,r} \qquad (9)$$

where

$A_{u,cult,r}$ is the initial area of available cultivable land being utilised (see **Fig. 2**)

$q_{o,cult,r}$ is the relative change in available cultivable land being utilised (GTAP output)

The change in wheat production caused by expansion in the scenario country ($\Delta Q_{E,wht,r}$) is calculated from

$$\Delta Q_{E,wht,r} = \Delta A_{u,cult,r} \cdot Y_{wht,r} \qquad (10)$$

where

$Y_{wht,r}$ is the initial wheat yield per hectare where *r* is the scenario country

The change in wheat production caused by displacement of other crops in the scenario country ($\Delta Q_{C,wht,r}$) is calculated from

$$\Delta Q_{C,wht,r} = (\Delta A_{u,cult,wht,r} - \sum \Delta A_{u,cult,c,r}) \cdot Y_{wht,r} \quad (11)$$

where

$\Delta A_{u,cult,wht,r}$ is the change in area in the wheat sector where *r* is the scenario country

$\sum \Delta A_{u,cult,c,r}$ is the sum of area changes in all crop sectors where *r* is the scenario country

The change in wheat production caused by livestock displacement in the scenario country ($\Delta Q_{L,wht,r}$) is calculated from

$$\Delta Q_{L,wht,r} = \Delta Q_{A,wht,r} - \Delta Q_{E,wht,r} - \Delta Q_{C,wht,r} \qquad (12)$$

where

$\Delta Q_{A,wht,r}$ is the total change in wheat production where r is the scenario country

The net expansion on grazable land in a region ($\Delta A_{u,graz,r}$) is calculated from

$$\Delta A_{u,graz,r} = A_{u,graz,r} \cdot q_{o,graz,r} \qquad (13)$$

where

$A_{u,graz,r}$ is the initial area of available grazable land being utilised (see **Fig. 2**)

$q_{o,graz,r}$ is the relative change in available grazable land being utilised (GTAP output)

Data on production (Q) of milk and meat (bovine, equine, sheep and goat) in 2001 is retrieved from FAOSTAT (2007) for all countries available (155). These data are sorted in GTAP regions (index r) and GTAP livestock sectors (index l).

The total change in production in a livestock sector ($\Delta Q_{l,r}$) is calculated from

$$\Delta Q_{l,r} = Q_{l,r} \cdot q_{o,l,r} \qquad (14)$$

where

$Q_{l,r}$ is the initial production in livestock sector l (FAOSTAT data)

$q_{o,l,r}$ is the relative change in production in livestock sector l (GTAP output)

13.3 Article 3: Biomes Affected by Agricultural Expansion

Kløverpris J (2009): *Identification of biomes affected by marginal expansion of agricultural land use induced by increased crop consumption*, Journal of Cleaner Production 17, 463-470.

Journal of Cleaner Production 17 (2009) 463–470

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Identification of biomes affected by marginal expansion of agricultural land use induced by increased crop consumption

Jesper Hedal Kløverpris [a,b,*]

[a] Department of Management Engineering, Section for Innovation and Sustainability, Technical University of Denmark, Produktionstorvet 424, DK-2800 Lyngby, Denmark
[b] Novozymes A/S, Krogshøjvej 32, DK-2880 Bagsværd, Denmark

ARTICLE INFO

Article history:
Received 5 March 2008
Received in revised form
4 August 2008
Accepted 12 August 2008
Available online 1 October 2008

Keywords:
Life cycle assessment
Agriculture
Life cycle inventory

ABSTRACT

In a previous study, the global agricultural expansion caused by wheat consumption in four different countries was modelled with the aim of establishing land use life cycle inventories. The previous study estimated the areas affected by expansion (in terms of square meters) but did not explain how to characterise these areas. The present study ascribes so-called biomes (natural potential vegetation) to the areas affected by agricultural expansion in order to provide a basis for assessing the environmental impacts from land use in the life cycle impact assessment (LCIA). The methodology builds on agricultural statistics and maps of global agricultural areas and the global distribution of biomes. The application of the method is illustrated with four examples. The results indicate that agricultural expansion on land suited for crop cultivation (cultivable land) typically affects forest biomes or potential grassland/steppe, whereas expansion on land suited for grazing but not for crop cultivation (grazable land) typically occurs on potential shrubland or a few other biomes depending on the region. Some uncertainty applies to the results but it is concluded that it is feasible to identify biomes affected by agricultural expansion and that the biomes can therefore be used as a starting point for land use LCIA.

1. Introduction

Human land use activities influence ecosystems of the globe immensely [1] and therefore the inclusion of land use impacts is essential for the relevance of the life cycle impact assessment (LCIA) when product systems with influence on land use are analysed. Without knowing the size and the characteristics of the land systems ultimately affected by a given action, it is not possible to determine the environmental impacts of such an action. However, a consensus on the land use methodology in life cycle assessment (LCA) is yet to be established. So far, most research has focused on life cycle impact assessment (LCIA). Lindeijer [2] summarises several proposals for land use LCIA methods. Most of these methods take their point of departure in a common framework describing land occupation and transformation in a coordinate system with time, land quality, and area on respectively the first, second, and third axis. Milá i Canals et al. [3] developed this framework further, e.g. by introducing the so-called dynamic reference situation. The methodological framework for land use LCIA has been the subject of much discussion and so has the choice of a land quality indicator, which is necessary for the practical application of the framework. Vogtländer et al. [4] and Milá i Canals et al. [5] contribute to this discussion by proposing respectively botanical value and soil organic matter as appropriate indicators. Köllner and Scholz [6,7] develop another version of the common framework and use species diversity as a quality indicator. Furthermore, Michelsen [8] proposes a procedure for measuring land quality in terms of biodiversity.

Whereas much focus has been on land use LCIA, less attention has been paid to its precondition, namely modelling of the land use LCI (life cycle inventory). The current land use LCIA methods are therefore often applied to areas, which do not represent the land actually or ultimately affected by the changes typically studied in LCA. In other cases, the land use LCIA methods are tested on hypothetical land use changes with no or only vague relations to an actual environmental product assessment (the typical LCA), which means that basic mechanisms of land markets are ignored. For instance, Antón et al. [9] applied two different LCIA methods to five types of land use in a specific Spanish location but, due to the hypothetical nature of the study, no consideration was given to side effects caused by the so-called replacement mechanisms. Some authors, however, do acknowledge that a decision or action that influences land use in one location may have effects on land use in other locations. Mattsson et al. [10] point out that, due to international trade, Europeans can influence land use in other regions of the world. Furthermore, Vogtländer et al. [4] stress that the environmental impacts of increasing land use depend on where the

* Department of Management Engineering, Section for Innovation and Sustainability, Technical University of Denmark, Produktionstorvet 424, DK-2800 Lyngby, Denmark. Tel.: +45 4446 0263.
E-mail address: JKlp@novozymes.com

0959-6526/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2008.08.011

change in land use is located. This is also acknowledged by Schmidt [11] who indentifies Canada as the country ultimately affected by the increased consumption of wheat in Denmark. Kløverpris et al. [12,13] explore the mechanisms of crop production further and demonstrate how economic modelling can be used to estimate the global agricultural expansion caused by consumption of 1 ton of wheat in a given country. However, quantification of the expansion is not enough to provide a basis for land use LCIA. Characterisation of the areas affected by expansion in the different regions of the world must also be performed. With a global scope, it is however difficult to determine the location of these areas exactly. This calls for a characterisation measure which has a relatively coarse geographic distribution in order to reach a robust conclusion on the characteristics assigned to the affected areas (in preparation for LCIA[1]). Eco-regions[2] have been mentioned as a suitable scale of analysis for land use impacts in LCA [15] but, with 825 different eco-regions, the present study requires a more aggregated characterisation measure. Biomes, which can be described as a coarse classification of *potential natural vegetation*, meet this requirement.

The purpose of the present paper is to present and demonstrate a method for identifying the biomes affected by agricultural expansion within a given region.

2. Methodology

Kløverpris et al. [13] estimate the global agricultural expansion caused by marginal wheat consumption (synonymous with increased wheat demand) in respectively Brazil, China, Denmark, and USA. The simulations are performed with a modified version of the economic equilibrium model called GTAP (Global Trade Analysis Project). In this model, the world is split into 22 regions, and the results show that, for the four countries investigated, more than 90% of the modelled global expansion occurs in the eight regions listed in Table 1. These results are specific to the simulations of increased wheat demand. For another crop, the distribution of affected regions may be different. For instance, a simulation of increased oil crop demand, say in xeu15, would probably have caused South East Asia to be among the most affected regions because of the palm oil production in Malaysia and Indonesia.

The codes in Table 1 will be used in the text when referring to the regions. The first four regions (xeu15, xsu, xla, and xss) are *multi country regions* whereas the last four (aus, bra, can and usa) are *single country regions*. The methodology presented in the present paper has evolved around the identification of biomes affected by agricultural expansion in these eight regions. The reason why Denmark is not included in the region with the remaining EU15 countries (xeu15) is that Denmark was one of the four countries for which increased domestic wheat production was investigated by Kløverpris et al. [13].

2.1. Land types and expansion

In the economic model used by Kløverpris et al. [13], each region has two types of land suitable for agricultural production:

1. *Cultivable land*: This land type can be used as cropland and for pastures. The suitability for these purposes is determined by Ramankutty et al. [16] who examined existing relationships between cropland, climate indices, and soil characteristics. The suitability for agricultural land use does not relate to productivity but only to whether climate and soil constraints allow for cultivation.
2. *Grazable land*: This land type can be used for pastures, but not as cropland. It is defined by Kløverpris et al. [13] as land which is not cultivable and not desert. It is thereby assumed that any land which is not fertile enough for cultivation but more fertile than a desert can support livestock grazing at some level. Consequently, the definition does not relate to the productivity of the land, but only the suitability (corresponding to the other land type definition).

Table 1
The eight regions representing more than 90% of the global agricultural expansion caused by wheat consumption in respectively Brazil, China, Denmark, and USA [13]

Code	Region
xeu15	EU15 excluding Denmark
xsu	Former Soviet Union excluding the Baltic states
xla	South America excluding Brazil and Peru
xss	Sub-Saharan Africa excluding SACU[a]
aus	Australia
bra	Brazil
can	Canada
usa	USA

[a] South African Customs Union: Botswana, Lesotho, Namibia, South Africa, and Swaziland.

The majority of the agricultural expansion modelled by Kløverpris et al. [13] takes place on cultivable land (see Fig. 1). There are, however, two exceptions. In USA, expansion only takes place on grazable land (as the cultivable land is already fully utilised). In xsu, the distribution between the expansion on the two land types is more or less equal. In the rest of the regions, more than two-thirds of the expansion takes place on cultivable land, except in xeu15 where it is roughly 60%.

It is important to distinguish between land *type* and land *use*. Land type (cultivable or grazable land) is based on natural characteristics (soil and climate) whereas land use is determined by the exploitation of the land. Cropland and pastures constitute land uses. Nature is simply land, which is not being significantly influenced by direct human use and therefore possesses its natural potential vegetation (biome). Fig. 2 demonstrates how the two land types can 'move' between agricultural land uses and nature. Note that the double arrows do not indicate a hectic change forth and back. They only illustrate the possible directions for the evolution in agricultural land use.

Kløverpris et al. [12,13] introduce two types of agricultural expansion. The reason is that the expansion predicted as a result of increased wheat consumption must be seen in relation to the trend

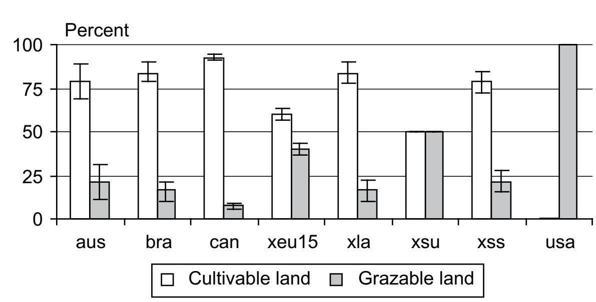


Fig. 1. Regional ratios between the expansion on cultivable and grazable land caused by increased wheat consumption in respectively Brazil, China, Denmark, and USA [13]. Full bars indicate the average ratios, and error bars indicate the highest and lowest ratios for the four simulations of wheat consumption.

[1] The inventory analysis is the preparation for LCIA. For land use, the size and the characteristics of affected areas must be determined in order to carry out LCIA.

[2] Olson et al. [14] define eco-regions as '*relatively large units of land that contain a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of the natural communities prior to major land use change*'.

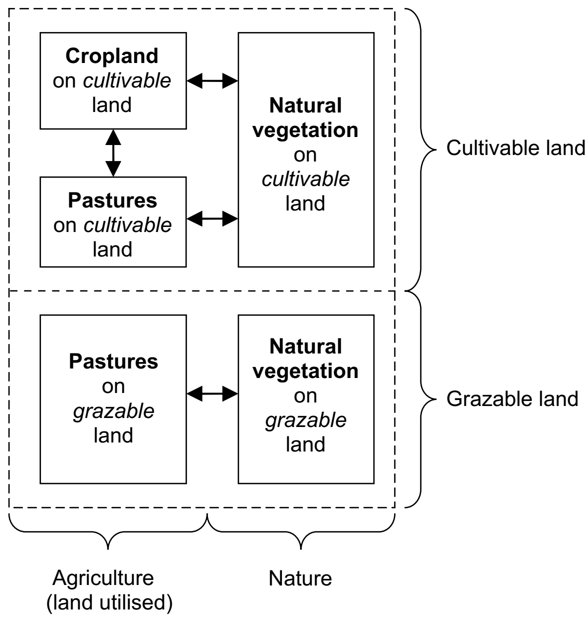


Fig. 2. Illustration of possible changes in the utilisation of cultivable and grazable land. Land not available for agricultural production is not shown.

in agricultural areas. If expansion is predicted in a region that already has a positive (growing) trend in its agricultural land use, the predicted expansion is interpreted as an acceleration of the ongoing expansion and consequently designated *accelerated transformation*. This type of expansion leads to the transformation of an area before it would otherwise have happened. The other type of expansion takes place in regions with a decreasing trend in its agricultural areas. In such regions, the predicted expansion constitutes a delay in agricultural abandonment. This type of expansion is consequently designated *delayed relaxation*.

2.2. Identification of trends in the utilisation of the two land types

The agricultural expansion estimated by Kløverpris et al. [13] occurs partly on cultivable land, and partly on grazable land (see Fig. 1). In order to determine the type of expansion (accelerated transformation or delayed relaxation) on each of the two land types, it is necessary to analyse the trend in the utilisation of the land types in the relevant region. Utilisation is defined for each of the two land types as the share (percent) of the land type being utilised for agricultural purposes within the region [13].

The trend in utilisation determines not only the type of expansion but also *where* expansion takes place within the relevant region. If the utilisation trend is negative, expansion will be constituted by delayed relaxation of land in areas where utilisation of the relevant land type is falling. If the utilisation trend is positive, expansion on the land type will be accelerated and located where expansion is already taking place. In both situations, expansion will occur on the frontier between agriculture and nature (assuming that agricultural abandonment releases land to nature). In other words, focus is on the margin of the agricultural area. This is in agreement with the consequential approach in LCA, which is based on marginal data (see e.g. Ekvall and Weidema [17]) and which is also the premise of the identification of the region where the expansion takes place [13].

Kløverpris et al. [13] establish utilisation data for cultivable and grazable land in different countries and regions of the world. This is done by an electronic overlay of a global map with cultivable land [18] and a global map with cropland and pastures [19]. For cultivable land, the utilisation data are split between cropland utilisation and pasture utilisation. To demonstrate, aggregated utilisation data for the eight regions of interest in this study are shown in Table 2.

Unfortunately, the maps used for the elaboration of the utilisation level are only available for one point in time (around year 2000). Consequently, the trends in utilisation of the two land types cannot be determined on this basis alone. The yearly development in agricultural land use (cropland and pasture areas) within the latest 10 year period, as available in FAOSTAT [20], is therefore used as a supplement to the utilisation data. The assessment of the utilisation trends for the two land types (cultivable and grazable land) is based on the following assumptions.

Assumption 1: If the cropland area in a region is increasing, the utilisation trend for cultivable land is positive.

Assumption 1 is applied even if data suggest that some of the increase in cropland area is caused by the conversion of pastures to cropland, which would have a neutral effect on the utilisation of cultivable land (see Fig. 2). The reasoning is that if the demand for crops is strong enough to cause conversion of pastures (on cultivable land) to cropland, there will also be incentives to transform natural land to cropland. Obviously, this assumption is not valid if the total utilisation of cultivable land is already very high. This must be judged on a case-by-case basis.

Assumption 2: If a region's cropland and pasture areas are both increasing, the utilisation trend for both cultivable and grazable land is positive.

It is possible to construct a couple of examples that are in contradiction with assumption 2 but both are highly unlikely and will not be considered in this paper.

Assumption 3: If a region's cropland and pasture areas are both decreasing, the utilisation trend for both cultivable and grazable land is negative.

If both cropland and pasture areas are decreasing, cultivable land is not likely to be converted from pastures to cropland, i.e. the utilisation trend for cultivable land is negative. As for grazable land, this is assumed to be released from pasture utilisation before cultivable land (c.f. Fig. 2) because grazable land is less fertile. Thus, the utilisation trend for grazable land will also be negative if both types of agricultural land use are decreasing.

These three assumptions are used as general guidelines in the assessment of land type utilisation trends within the regions, and their validity is judged from case to case, especially in relation to the known utilisation data (around year 2000) for the two land types. The assumptions are supplemented with considerations on the rate at which the development in respectively cropland and

Table 2
Utilisation of cultivable and grazable land (around year 2000) for the eight regions of interest in the present study

	xeu15	xla	xsu	xss	aus	bra	can	usa
Total area (10^6 Ha)	321	816	2188	2165	785	853	993	944
Cultivable land available[a] (10^6 Ha)	108	184	452	518	147	235	61	259
Grazable land available[a] (10^6 Ha)	125	174	1386	870	254	421	756	246
Utilisation of cultivable land, cropland	71%	29%	43%	29%	16%	20%	59%	69%
Utilisation of cultivable land, pastures	21%	53%	45%	47%	48%	47%	11%	31%
Utilisation of cultivable land, total	92%	82%	88%	76%	64%	67%	70%	100%
Utilisation of grazable land, pastures	20%	84%	11%	41%	81%	17%	2%	62%

[a] The term 'available' indicates that the land is not protected, is not covered by human settlements, and does not have a steepness above 30%. The estimates include the entire area available for agricultural use (utilised + unutilised).

pasture areas takes place. For instance, if the pasture area is decreasing at a faster rate than an ongoing increase in the cropland area, pastures are assumed to be converted partly to cropland (provided that some cultivable land is utilised as pastures) and partly to nature. As discussed above, pastures released to nature are assumed to be on grazable land. Thus, the utilisation trend for grazable land would be decreasing in the example described. More examples of such deductions are given in Section 3.

2.3. Identifying biomes affected by expansion on cultivable land

Based on the utilisation trend for cultivable land, the location of expansion on this land type within the relevant region is determined. It is assumed that the location of expansion on cultivable land is indicated by recent changes in cropland areas. In principle, recent changes in pasture areas could *also* indicate changes in the use of cultivable land. Meanwhile, cropland expansion is the dominant or sole contributor to the total expansion on cultivable land modelled by Kløverpris et al. [13] (see Fig. 3). This does not completely justify the assumption that recent changes in croplands can be used as an indication of the frontier between agriculture and nature on cultivable land or, in other words, the location affected by agricultural expansion on this land type. However, it does indicate that the majority (if not all) of the modelled expansion on cultivable land will take place where recent changes in the cropland area have been observed. The methodology thereby captures the main areas affected by expansion on cultivable land. Furthermore, it is likely that if a region experiences expansion of both cropland and pastures on cultivable land, then the same biomes will be affected by both land uses. In that case, the possible error is cancelled. The procedure for identifying biomes affected by expansion on cultivable land depends on the type of region being studied.

2.3.1. Expansion on cultivable land in multi country regions

For multi country regions with a positive trend in the utilisation of cultivable land, the individual countries with an increasing cropland area (based on the latest 10 year period available in FAOSTAT [20]) are identified as the areas affected by expansion (disregarding countries already utilising all of their cultivable land). Analogously, individual countries with a decreasing cropland area are identified as the areas affected by expansion in regions with a negative trend in the utilisation of cultivable land. For large countries, comparison of cropland maps from 1970 and 1990 is used to identify the areas affected by the net expansion on cultivable land (procedure described in Section 2.3.2).

2.3.2. Expansion on cultivable land in single country regions

As FAOSTAT [20] only provides data at the country level, the procedure described above cannot be used to locate areas affected by expansion within a single country region. Instead, maps of global cropland distribution in respectively 1970 and 1990 [18] are compared by use of a GIS tool to locate areas with changes. For a region with a positive utilisation trend for cultivable land, areas with increasing croplands are identified as the locations affected by expansion. Analogously, areas with decreasing croplands should be identified as the locations affected by expansion in regions with a negative utilisation trend for cultivable land. Meanwhile, decreases in the cropland areas from 1970 to 1990 have not been very common in the relevant single country regions in this study. So, unless areas with a decrease in croplands can be identified, areas with increasing croplands are also used to indicate the areas affected by expansion in single country regions with a negative utilisation trend for grazable land. The reason is that areas affected by change, in general, are assumed to be those on the margin of the agricultural area.

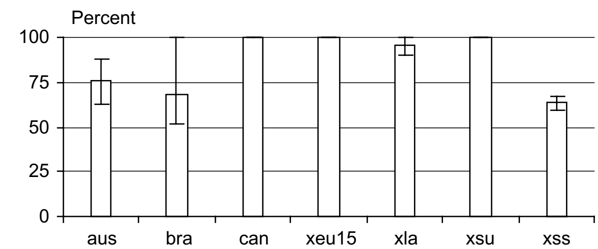


Fig. 3. Regional contribution of cropland expansion to the total expansion on cultivable land caused by wheat consumption in respectively Brazil, China, Denmark, and USA [13]. Full bars indicate the average contribution, and error bars indicate the highest and lowest contributions for the four simulations of wheat consumption. The remaining share of total expansion on cultivable land is constituted by pasture expansion. USA is excluded as no expansion occurs on cultivable land in that region (due to full utilisation of that land type).

2.3.3. Determining the biomes affected

The locations of the areas affected by expansion on cultivable land (in both region types) are transferred to a biome map with a global overview of 15 potential natural vegetation types [18]. The affected biome is thereby determined for cultivable land. If several biomes appear to be affected, the expansion is split between these biomes in an approximate ratio (e.g. 50% of biome 1 and 50% of biome 2). Data on cropland by regions and biomes [19] are used to cross-check the conclusions if necessary.

2.4. Identifying biomes affected by expansion on grazable land

It is assumed that the location of the expansion on grazable land (as predicted by Kløverpris et al. [13]) is indicated by recent changes in pasture areas. In principle, such changes could also indicate changes in the use of cultivable land. However, if the pasture area in a given region is decreasing, grazable land is assumed to be released from agriculture before cultivable land as the latter is more fertile (also discussed in relation to assumption 3 in Section 2.2). On the other hand, if the pasture area in a given region is increasing, it may in fact happen on cultivable land. This is accounted for by disregarding cropland biomes, i.e. biomes already characterised as cultivable land in the relevant region. This procedure is explained in more detail for the two types of regions being studied.

2.4.1. Expansion on grazable land in multi country regions

For multi country regions with a positive trend in the utilisation of grazable land, individual countries with an increasing pasture area (based on the latest 10 year period available in FAOSTAT [20]) are identified as the areas affected by expansion. For regions with a negative trend in the utilisation of grazable land, countries with decreasing pasture areas [20] are identified as the locations where expansion occurs (as delayed relaxation). Biomes are identified on the biome map and those considered cultivable land are discarded (as described above). If more than one biome is affected, the expansion is split between them as also described in Section 2.3.3.

2.4.2. Expansion on grazable land in single country regions

Biomes affected by expansion on grazable land are identified by the use of a global pasture map, which may be supplemented with a global map showing both pastures and cropland [19]. The maps are used to study the distribution of pastures in the relevant region. The frontier between pastures and nature is thereby assessed and the location is then identified on the global biome map. This reveals the biomes used for pastures (pasture biomes). Among these biomes, those previously identified as cropland biomes (and thereby cultivable land) are discarded.[3] As the pasture maps do not reveal any development over time, the utilisation trend for grazable land does not influence the identification of the areas affected by expansion on grazable land in single country regions (only the type of expansion).

Data on pastures by regions and biomes [19] are used to cross-check the conclusions for both region types.

3. Examples and results

To demonstrate the practical application of the methodology, examples are presented for two multi country regions and two single country regions. The application to the other four regions listed in Table 1 is shown in Supplementary information. As explained in Section 2, the identification of biomes affected by agricultural expansion is mainly based on two types of data, namely the development in agricultural land use (cropland and pastures) as described by FAOSTAT [20] and the utilisation levels for cultivable and grazable land around year 2000 (Table 2).

3.1. Sub-Saharan Africa excluding the South African Customs Union (xss)

3.1.1. Utilisation trends for the two land types

As both croplands and pasture areas are increasing in xss (see Fig. 4), it is assumed that the utilisation of both cultivable and grazable land is increasing (see assumption 2).

3.1.2. Biomes affected by expansion on cultivable land

All countries in the region with full or almost full utilisation of cultivable land (Ghana, Rwanda, Côte d'Ivoire, Gambia, Tanzania, and Uganda) are excluded as candidates for locations affected by expansion. Among the remaining countries, Benin, Burkina Faso, Guinea, Kenya, Malawi, Mozambique, and Sierra Leone show an increase in their cropland area from 1994 to 2003 [20]. Several of the countries with the most significant increase in cropland area lie in western Africa on the southern coast. This area is mainly dominated by tropical evergreen forest but also savanna. According to Ramankutty et al. [19], both of these vegetation types are used as cropland in Africa. Expansion on cultivable land in this region can therefore be expected to affect both biomes. The question is then how to split the expansion between them (see Section 2.3.3). The dominance of forest in the affected areas indicates that this biome will be more affected than savanna. On the other hand, the data on cropland by regions and biomes [19] show that much more savanna/grassland in Africa has been converted to cropland in the past compared to forests. This indicates that savanna will be more affected. In other words, there is more forest than savanna but there is an apparent tendency to prefer the latter. Combining this information, it is assumed that cropland expansion takes place on equal shares of savanna and tropical evergreen forest.

3.1.3. Biomes affected by expansion on grazable land

According to FAOSTAT [20], Burundi, Djibouti, Mali, and Niger have experienced a significant and relatively steady increase in pasture areas from 1994 to 2003. Djibouti has full utilisation of grazable land, so this country is disregarded. The largest absolute pasture expansion is seen in Mali and Niger. These are already using most of their cultivable land (80% and 96% utilisation, respectively), so it is most likely that pasture expansion is taking place on grazable land (51% and 48% utilisation, respectively). Since forest and savanna/grassland seem to be suited for crops in Africa (cultivable land), it is assumed that pasture expansion takes place on open shrubland. The relatively small pasture expansion taking place in Burundi is thereby ignored.

In summary, agricultural expansion on cultivable land in xss is assumed to affect equal shares of tropical evergreen forest and savanna (accelerated transformation) whereas expansion on grazable land is assumed to affect open shrubland (accelerated transformation).

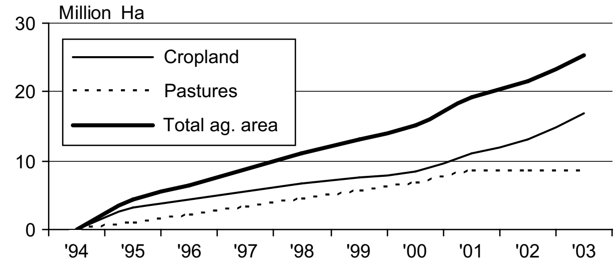


Fig. 4. Trend in agricultural areas in xss (Sub-Saharan Africa excluding the South African Customs Union). Reference year: 1994 [19].

3.2. EU15 excluding Denmark (xeu15)

3.2.1. Utilisation trends for the two land types

Areas of both cropland and pastures in xeu15 are decreasing (see Fig. 5). Pasture area is decreasing faster than cropland area, which means that the decrease in pastures cannot be explained only by the conversion of pastures to cropland. The utilisation of cultivable land is therefore assumed to be decreasing and so is the utilisation of grazable land (in accordance with assumption 3).

3.2.2. Biomes affected by expansion on cultivable land

The largest absolute changes in cropland area in EU15 from 1996 to 2005 were constituted by significant decreases in Italy, Portugal and Spain [20]. The potential natural vegetation in these countries is evergreen deciduous mixed forest (Italy) and dense shrubland (Portugal and Spain). The fact that the largest changes in cropland areas in the period mentioned took place in Italy, Portugal, and Spain does not mean that *all* expansions necessarily will occur as delayed release in these three countries. However, it is a good indication that the *majority* of the expansion will take place here. It is therefore assumed that agricultural expansion on cultivable land will affect equal shares of evergreen deciduous mixed forest and dense shrubland.

3.2.3. Biomes affected by expansion on grazable land

From 1996 to 2005, significant decreases in pasture areas have been observed in most EU15 countries, especially France, Germany, Greece, and Spain [20]. Some of the EU15 pastures are on cultivable

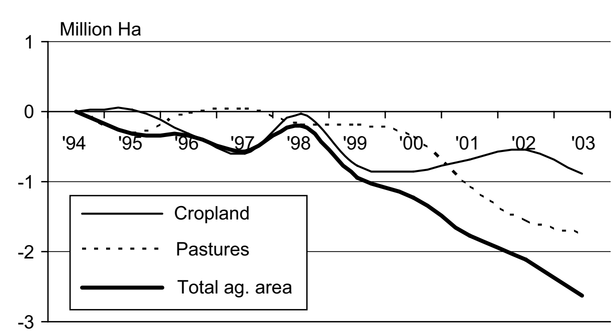


Fig. 5. Development in agricultural areas in xeu15 from 1994 to 2003. Reference year: 1994 [19].

[3] Exception: in the case of xeu15, a specific biome (potential dense shrubland) is assumed to constitute both cultivable and grazable land (interpreted as different soil qualities within the same biome). See Section 3.2.

land (see Table 2). Actually, more than 80% of the pastures in Europe are on potential forest [19]. Presumably, most of this is cultivable as more than three quarters of Europe's cropland is also on potential forest [19]. It is therefore assumed that expansion on grazable land will take place on potential dense shrubland primarily available in Spain but also in Italy and Greece (respectively, 9%, 17%, and 4% utilisation of grazable land).

In summary, agricultural expansion on cultivable land in xeu15 is assumed to affect equal shares of evergreen deciduous mixed forest and dense shrubland (delayed relaxation) whereas agricultural expansion on grazable land is assumed to affect dense shrubland (delayed relaxation).

It may seem strange that potential dense shrubland is assumed to be affected by expansion on both land types. This can be interpreted as different soil qualities within the same biome. In Spain, for instance, most of the country is potential dense shrubland (according to the biome map) and more than a third of the country is cropland [20]. Thus, parts of the potential dense shrubland must be cultivable.

3.3. Australia (aus)

3.3.1. Utilisation trends for the two land types

The cropland area in Australia is increasing while the pasture area is decreasing (see Fig. 6). The decrease in pastures occurs at a (numerically) higher rate than the increase in croplands. This is interpreted as pastures being converted partially to cropland, and partially to nature. The pastures converted to nature are assumed to be on grazable land (see Section 2.4) and, therefore, the utilisation of grazable land is assumed to be decreasing. On the other hand, the utilisation of cultivable land is assumed to be increasing (see *Assumption 1* in Section 2.2).

3.3.2. Biomes affected by expansion on cultivable land

As described in Section 2.3, changes in cropland area are assumed to indicate where expansion on cultivable land takes place. Since Australia appears to have a positive utilisation trend for cultivable land, areas which have experienced an increase in croplands are identified. This is done by comparing the cropland maps from 1970 and 1990 (see Section 2.3). The comparison shows an increase in cropland area in the south-western, mid-southern, south-eastern, and mid-eastern parts of Australia. The biomes of these four areas are mainly potential savanna and, for the south-west and mid-east, also shrublands. As potential savanna is the dominating biome in the areas identified, it is assumed that expansion on cultivable land takes place on this potential vegetation type.

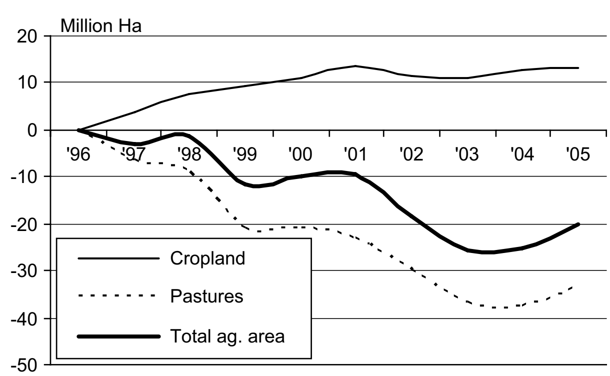


Fig. 6. Development in agricultural areas in Australia from 1996 to 2005. Reference year: 1996 [19].

3.3.3. Biomes affected by expansion on grazable land

To identify the biomes affected by expansion on grazable land, the pasture map (see Section 2.4.2) is used to determine the distribution of pastures in Australia. Pastures are most abundant in the eastern third of the country, which is mainly dominated by potential savanna but also potential dense shrubland, open shrubland, and grassland/steppe (in descending order). Furthermore, a significant part of Australia's pastures is present in the west, which is dominated by potential open shrubland. Due to the dominance of pastures on open shrubland and grassland/steppe, it is assumed that the expansion of pastures takes place on 50% open shrubland and 50% grassland/steppe. This is in good correlation with the current distribution of pastures on biomes in the developed Pacific [19].

In summary, agricultural expansion on cultivable land in Australia is assumed to affect savanna (accelerated transformation) whereas agricultural expansion on grazable land is assumed to affect equal shares of open shrubland and grassland/steppe (delayed relaxation).

3.4. Brazil (bra)

3.4.1. Utilisation trends for the two land types

Both cropland and pasture areas are increasing in Brazil (see Fig. 7) and it is therefore assumed that the trend in utilisation of both cultivable and grazable land is positive (see *Assumption 2* in Section 2.2).

3.4.2. Biomes affected by expansion on cultivable land

Comparison of the cropland maps shows that from 1970 to 1990, the expansion of croplands mainly took place in the central and eastern part of Brazil. Meanwhile, the maps also show that cropland expansion is moving west (further) into the Amazon Basin, which appears to constitute the largest expansion potential in the country. Therefore, expansion on cultivable land is assumed to take place on potential tropical evergreen forest (based on the biome map).

3.4.3. Biomes affected by expansion on grazable land

According to the pasture maps (see Section 2.4.2), pastures are concentrated in the south-western part of Brazil. This area is dominated by potential savanna, tropical deciduous forest and some tropical evergreen forest. In fact, recent years have shown considerable conversion of tropical forest to pastures but this is judged to be expansion on cultivable land (see above). The expansion on grazable land is therefore assumed to take place on savanna.

In summary, agricultural expansion on cultivable and grazable land in Brazil is assumed to affect respectively tropical evergreen forest and savanna (accelerated transformation).

3.5. All eight regions of interest

The biomes affected by the agricultural expansion estimated by Kløverpris et al. [13] are listed for the eight regions of interest in

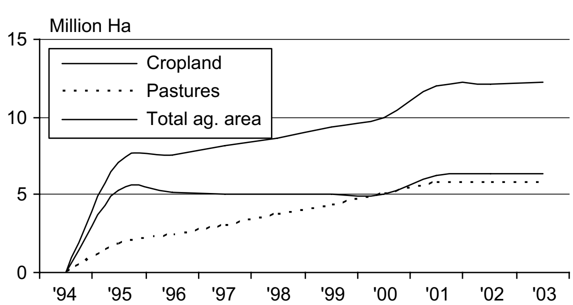


Fig. 7. Development in agricultural areas in Brazil from 1994 to 2003. Reference year: 1994 [19].

Table 3
Biomes affected by agricultural expansion in terms of accelerated transformation or delayed relaxation followed by 1 year of occupation

Region	Potential vegetation affected on cultivable land	Potential vegetation affected on grazable land
aus	Savanna (accelerated transformation)	Open shrubland + grassland/steppe (delayed relaxation)
bra	Tropical evergreen forest (accelerated transformation)	Savanna (accelerated transformation)
can	Boreal deciduous forest (delayed relaxation)	Boreal evergreen forest (delayed relaxation)
xeu15	Evergreen/deciduous mixed forest + dense shrubland (delayed relaxation)	Dense shrubland (delayed relaxation)
xsu	Grassland/steppe (delayed relaxation)	Evergreen/deciduous mixed forest (delayed relaxation)
xla	Grassland/steppe + tropical evergreen forest (accelerated transformation)	Savanna + dense shrubland (delayed relaxation)
xss	Tropical evergreen forest + savanna (accelerated transformation)	Open shrubland (accelerated transformation)
usa	(Not relevant)	Open shrubland (delayed relaxation)

If two biomes are mentioned for the same region, expansion is expected to affect equal shares.

Table 3 together with the type of expansion. As can be seen from the table, agricultural expansion on cultivable land typically occurs on forest biomes or potential grassland/steppe. In a couple of cases, savanna is also affected. Agricultural expansion on grazable land typically occurs on potential shrubland although other biomes are also affected depending on the region.

4. Discussion of the uncertainties related to the identification of biomes affected by agricultural expansion

The method presented and exemplified in this paper draws upon quantitative data on the development in agricultural land use and the global distribution and utilisation of cultivable and grazable land. Besides these quantitative frames, the method is characterised by qualitative judgements based on a number of assumptions. For some of the regions assessed, it is quite simple to perform a plausible identification of the biomes affected by agricultural expansion whereas it is much more difficult and uncertain for others. Based on the experience with the eight regions studied, this section discusses the certainty of the conclusions reached for each region. Two aspects will be considered, namely the assessment of the utilisation trends for the two land types and the identification of biomes affected by agricultural expansion. The certainty of the results is presented in Table 4.

The utilisation trends are considered relatively unambiguous for most of the regions. The reason is that the development in agricultural areas, as given by FAOSTAT [20], often gives a fairly good indication of the utilisation trends. Meanwhile, the data from FAOSTAT [20] rely on agricultural censes, which are performed with different frequencies in different countries. The data are thereby subject to some uncertainty, especially for the developing countries. Furthermore, degraded and unproductive pastures may be included in the statistics and thereby result in an overestimation of the effective pasture areas. Nevertheless, FAOSTAT [20] is the best identified source of worldwide agricultural statistics and that is why this database is used in the present study.

The identification of biomes affected by expansion is less certain compared to the assessment of the utilisation trends. The reason is that there may often be several biomes, which could potentially be affected and it is therefore necessary to make some crude assumptions to determine those *mainly* affected (c.f. the examples in Section 3). Nevertheless, there are often only a few of the 15 biomes that qualify as candidates for being affected by expansion on one of the land types and this, in itself, assures that the certainty is not below ‘moderate’.

Table 4
Certainty of the results for the eight regions studied

Region	Utilisation trends	Biomes affected
aus	Very good	Moderate
bra	Very good	Good
can	Moderate	Moderate
xeu15	Good	Moderate
xsu	Good/moderate	Moderate
xla	Moderate	Moderate
xss	Very good	Moderate/good
usa	Good	Moderate

‘Very good’ means that the result is considered unambiguous, ‘good’ indicates a high degree of certainty, and ‘moderate’ indicates some uncertainty about a result. The certainty is not considered ‘poor’ (or very uncertain) for any of the results.

Generally, the identification of biomes affected on grazable land is less certain than on cultivable land. Fortunately, expansion on cultivable land is more important because it constitutes the main share of the total expansion (see Fig. 1).

5. Conclusions and outlook

This paper presents an overall systematic approach for identifying biomes affected by the agricultural expansion on cultivable and grazable land modelled by Kløverpris et al. [13]. The paper also demonstrates the practical application of the method with four examples. As discussed in Section 4, there are some uncertainties in the identification of the relevant biomes. However, no better methodological alternatives are currently available and, in order to prepare for life cycle impact assessment (LCIA) of the areas affected by agricultural expansion, it is necessary to assign characteristics to these areas. Knowing the area itself (in terms of e.g. square meters or hectares) is not enough.

In this study, the natural potential vegetation represented by biomes is chosen as a suitable characteristic for the affected areas. The reason is that biomes have a relatively coarse geographic distribution, which fits the global scope of the analysis quite well. With 15 biomes distributed over the world in relatively large chunks, it is possible, although with the uncertainties discussed in Section 4, to obtain a rather good estimate of the nature types affected by agricultural expansion. In order to perform a full land use LCIA, it would, of course, be necessary to assign quantitative characteristics to each biome that could be used to describe the land quality of the biomes. These characteristics would depend on the LCIA method chosen and it is therefore beyond the scope of this paper to suggest such characteristics. Based on the exploration of the methodology described in Section 2, it is concluded that it is feasible to identify biomes affected by agricultural expansion, although with some uncertainty, and that the biomes can therefore be used as a starting point for land use LCIA.

To reduce the uncertainties discussed in Section 4, the land use modelling performed prior to the identification of the affected biomes could be modified. To begin with, the eight regions representing more than 90% of the agricultural global expansion could be disaggregated into smaller units. It would thereby be easier to identify the biomes affected in each region. The reason is that the smaller a region is, the less biomes it is likely to contain. Furthermore, the aggregation of regions in the land use modelling could be performed in accordance with the distribution of biomes. For instance, the countries in xeu15 could be split into smaller units according to the distribution of biomes in Europe. This would ease the challenge of identifying biomes affected by agricultural expansion in a specific region. Finally, disaggregated data on the development in cropland and pasture areas could be used for the single country regions, instead of the maps of cropland in 1970 and 1990 and the pasture maps. For instance, statistics for each single state in USA could be used.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi: 10.1016/j.jclepro.2008.08.011.

References

[1] Turner BL, Lambin EF, Reenberg A. The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Sciences 2007;104(52):20666–71.
[2] Lindeijer E. Review of land use impact methodologies. Journal of Cleaner Production 2000;8:273–81.
[3] Milá i Canals L, Bauer C, Depestele J, Dubreuil A, Knuchel RF, Gaillard G, et al. Key elements in a framework for land use impact assessment within LCA. International Journal of Life Cycle Assessment 2007;12(1):5–15.
[4] Vogtländer JG, Lindeijer E, Witte JPM, Hendriks C. Characterizing the change of land-use based on flora: application for EIA and LCA. Journal of Cleaner Production 2004;12:47–57.
[5] Milá i Canals L, Romanya J, Cowell SJ. Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in life cycle assessment (LCA). Journal of Cleaner Production 2007;15:1426–40.
[6] Köllner T, Scholz RW. Assessment of land use impacts on the natural environment. Part 1: an analytical framework for pure land occupation and land use change. International Journal of Life Cycle Assessment 2007;12(1):16–23.
[7] Köllner T, Scholz RW. Assessment of land use impacts on the natural environment. Part 2: generic characterization factors for local species diversity in central Europe. International Journal of Life Cycle Assessment 2008;13(1):32–48.
[8] Michelsen O. Assessment of land use impact on biodiversity. International Journal of Life Cycle Assessment 2008;13(1):22–31.
[9] Antón A, Castells F, Montero JI. Land use indicators in life cycle assessment. Case study: the environmental impact of Mediterranean greenhouses. Journal of Cleaner Production 2007;15:432–8.
[10] Mattsson B, Cederberg C, Blix L. Agricultural land use in life cycle assessment (LCA): case studies of three vegetable oil crops. Journal of Cleaner Production 2000;8:283–92.
[11] Schmidt JH. System delimitation in agricultural consequential LCA – outline of methodology and illustrative case study of wheat in Denmark. International Journal of Life Cycle Assessment 2008;13 LCA(4):350–64.
[12] Kløverpris J, Wenzel H, Nielsen PH. Life cycle inventory modelling of land use induced by crop consumption. Part 1: conceptual analysis and methodological proposal. International Journal of Life Cycle Assessment 2008;13(1):13–21.
[13] Kløverpris J, Baltzer K, Nielsen PH. Life cycle inventory modelling of land use induced by crop consumption. Part 2: example of wheat consumption in Brazil, China, Denmark, and the USA. International Journal of Life Cycle Assessment 2008 (under review).
[14] Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, et al. Terrestrial ecoregions of the worlds: a new map of life on Earth. Bioscience 2001;51:933–8.
[15] Milà i Canals L, Clift R, Basson L, Hansen Y, Brandão M. Expert workshop on land use impacts in life cycle assessment (LCA). International Journal of Life Cycle Assessment 2006;11(5):363–8.
[16] Ramankutty N, Foley JA, Norman J, McSweeney K. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Global Ecology and Biogeography 2002;11:377–92.
[17] Ekvall T, Weidema BP. System boundaries and input data in consequential life cycle inventory analysis. International Journal of Life Cycle Assessment 2004;9(3):161–71.
[18] Ramankutty N, Foley JA. Estimating historical changes in global land cover: croplands from 1700 to 1992. Global Biogeochemical Cycles 1999;13(4):997–1027.
[19] Ramankutty N, Evan AT, Monfreda C, Foley JA. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochemical Cycles, 22, GB1003. doi: 10.1029/2007GB002952.
[20] FAOSTAT statistical database. Rome, Italy: FAO, http://faostat.fao.org; 2007.

Identification of biomes affected by marginal expansion of agricultural land use induced by increased crop consumption Supporting information

This document is a supplement to a paper by Kløverpris [19] entitled 'Identification of biomes affected by marginal expansion of agricultural land use induced by increased crop consumption'. The present document reports on the application of the developed methodology to identify affected biomes in four of the eight regions studied. References to numbered sections and tables refer to the main paper by Kløverpris [19], in which the terminology is also explained and references to the literature can be found.

Canada (can)

Utilisation trends for the two land types: The cropland area in Canada is decreasing slightly (see **Fig. 8**). As the pasture area is also decreasing slightly, cultivable land is not assumed to be converted from pastures to cropland. This means that the utilisation trend for cultivable land is negative. As grazable land is assumed to be released from pastures first (see section 2.2), the utilisation of grazable land is also judged to be falling.

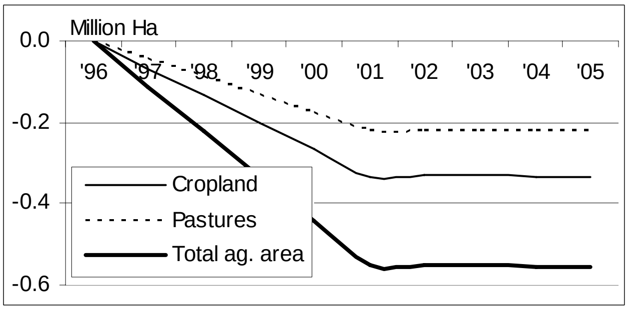


Fig. 8: Development in agricultural areas in Canada from 1996 to 2005. Reference year: 1996 [18]

Biomes affected by expansion on cultivable land: Judging from the cropland maps (see section 2.4.2), crops are not grown on areas with potential boreal evergreen forest implying that this biome is not found on cultivable land. However, expansion on croplands seems to have taken place in the Western part of Canada in areas with potential evergreen/deciduous mixed forest. The cropland expansion on this mixed biome must be taking place on the share constituted by potential *deciduous* forest and not on potential *evergreen* forest (as crops do not appear to grow on the latter). Thus, agricultural expansion on cultivable land in Canada is assumed to affect potential boreal deciduous forest.

Biomes affected by expansion on grazable land: Although Canada has a quite low utilisation of grazable land (see Table 2), almost two-thirds of Canada's pastures are on this land type (background data not shown). According to the pasture and cropland map (see section 2.4.2), the pastures in Canada are mainly located in the same areas as the croplands, i.e. on potential evergreen/deciduous mixed forest. As the deciduous part of this biome is assumed to be cultivable and the evergreen part is not (see previous paragraph), agricultural expansion on grazable land in Canada is assumed to take place on potential boreal evergreen forest.

In summary, agricultural expansion on cultivable and grazable land in Canada is assumed to affect respectively potential boreal deciduous forest and potential boreal evergreen forest (both in evergreen/deciduous mixed forest – as delayed relaxation).

Former Soviet Union excl. the Baltic States (xsu)

Utilisation trends for the two land types: The cropland area in xsu is decreasing while the pasture area is increasing (see **Fig. 9**). The cropland area is decreasing at a rate, which is numerically higher than the rate at which pastures are increasing. Thus, the utilisation trend for cultivable land is negative. When cultivable land is taken out of crop production, some of it is assumed to be converted to pastures. Furthermore, this conversion is assumed to release grazable land from pasture utilisation because more fertile land becomes available. In other words, the utilisation trend for grazable land in xsu is also assumed to be negative, despite the positive development in pasture areas.

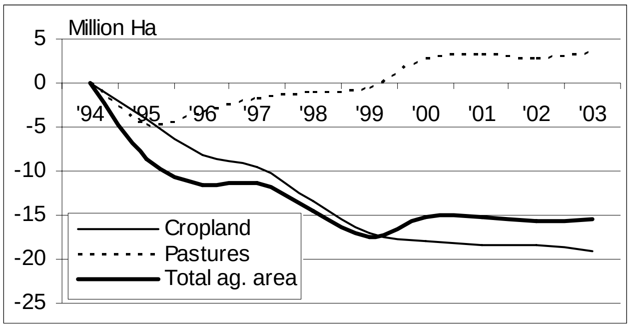


Fig. 9: Development in agricultural areas in xsu from 1994 to 2003. Reference year: 1994 [18]

Biomes affected by expansion on cultivable land: Due to the negative utilisation trend for cultivable land, countries in xsu with a decreasing cropland area are identified (see section 2.3.1). From 1994 to 2003, the largest absolute decreases in the cropland areas of xsu occurred in Kazakhstan, the Russian Federation, and Ukraine. For Kazakhstan, however, the decrease in cropland levelled out in 1999 [18] so this country will not be considered. To judge from the maps of cropland in 1970 and 1990, the main changes in Russian cropland areas from 1970 to 1990 took place on potential grassland/steppe. Thus, expansion on cultivable land is assumed to affect this biome in Russia. This is also considered the case for Ukraine, which possesses large areas of potential grassland/steppe according to the biome map (see section 2.3.3).

Biomes affected by expansion on grazable land: The densest areas of pastures in xsu are in Kazakhstan and the Russian Federation [17]. From 1994 to 2003, the largest absolute changes in pasture areas in xsu also occurred in these two countries [18]. However, the Kazakhstan pasture area stabilised around year 2000. Therefore, the areas affected by expansion on grazable land are expected to be found the Russian Federation. It should also be mentioned that the development in Russian agricultural areas as described by FAOSTAT [18] imply a decrease in the utilisation of grazable land (similar to that for the entire region). The pastures in Russia stretches out from two more or less parallel belts of potential savanna and grassland/steppe (presumably cultivable land as only two percent of Russia's grazable land is utilised) and into a more northerly area with potential evergreen/deciduous mixed forest (determined from comparison of the biome map and the cropland and pasture map, see section 2.3.3 and 2.4.2). The biome affected by expansion on grazable land in xsu is therefore believed to be evergreen/deciduous mixed forest.

In summary, agricultural expansion on cultivable and grazable land in xsu is assumed to affect respectively potential grassland/steppe and potential evergreen/deciduous mixed forest (delayed relaxation).

South America excl. Brazil and Peru (xla)

Utilisation trends for the two land types: The cropland area in xla was larger in 2003 than it was in 1994 although the overall increase was influenced by a decrease in Colombia [18]. The pasture area in xla was smaller in 2003 than it was in 1994. This development was heavily influenced by fluctuations in Colombia, which seem rather drastic compared to the rest of the region. Due to lack of confidence in the data for Colombia, this country has been excluded from the analysis. This does not change the overall development in cropland and pasture areas for xla. From 1994 to 2003, the cropland area in xla (excl. Colombia) has been increasing while the pasture area has been slightly decreasing (see **Fig. 10**). The shrinking pasture area is assumed to be caused partly by conversion to cropland (cultivable land) and partly by release to nature (grazable land). The utilisation trend for grazable land is therefore assumed to be negative. The utilisation trend for cultivable land is assumed to be positive due the increasing area of croplands (assumption 1).

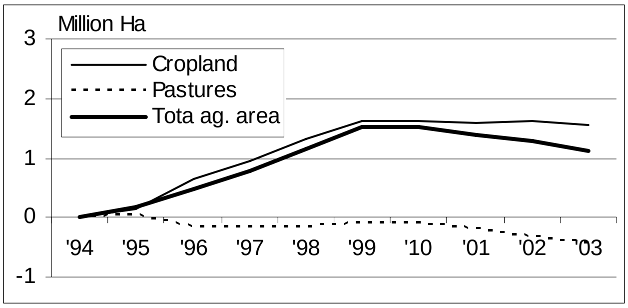


Fig. 10: Development in agricultural areas in xla excl. Colombia from 1994 to 2003. Reference year: 1994 [18]

Biomes affected by expansion on cultivable land: All countries with full utilisation of cultivable land (Argentina, Chile, and Ecuador) are discarded. This leaves Bolivia and Paraguay as the only countries in xla with an increasing area of croplands and an unutilised reserve of cultivable land (respectively 75 and 74 percent utilisation). Based on the biome map, it is assumed that expansion on cultivable land in Paraguay takes place on grassland/steppe. Bolivia is dominated by tropical evergreen forest and savanna, and it is assumed that the cultivable land mainly lies under the forest. On this basis, it is assumed that cropland expansion in xla takes place on equal shares of grassland/steppe and tropical evergreen forest.

Biomes affected by expansion on grazable land: The only four countries in xla with significant changes in their pasture area from 1994 to 2003 are Colombia, Ecuador, Falkland Islands, and French Guiana (decrease between 4 and 30 percent). The last two will be disregarded in this analysis due to their small size. Colombia and Ecuador are also disregarded for the following reasons: Colombia has a large reserve of grazable land (only 20% utilisation) but the data on pasture area from FAOSTAT [18] is fluctuating and probably not too reliable (also discussed above). Ecuador has full utilisation of both land types so further expansion in this country is not possible.

As the countries with ongoing changes in pasture areas (see above) do not appear to contain the biomes affected by further agricultural expansion on grazable land, countries with low utilisation of this land type are considered. Chile and Bolivia have large areas of unutilised grazable land and also large areas of pastures (overlay data, see section 2.2). Therefore, these two countries are able to respond to changes in the demand for grazable land.

Chile is dominated by potential dense shrubland, evergreen/deciduous mixed forest, and grassland/steppe. The country uses all of its cultivable land and 64% is used for pastures. Chile's most dense area of pastures is on potential evergreen/deciduous mixed forest and grassland/steppe. It is assumed that this is cultivable land (as these biomes are considered more fertile than dense shrubland). Thereby, the yet unutilised grazable land is assumed to be (mainly) dense shrubland.

As mentioned previously, Bolivia is dominated by tropical evergreen forest and savanna. Assuming potential tropical evergreen forest to be on cultivable land, agricultural expansion on grazable land in Bolivia will affect savanna. A simple 50/50 split between the affected biome in Chile and Bolivia is assumed.

It may seem strange that savanna is identified as the biome affected by expansion on grazable land in Bolivia. Savanna is identified as cultivable land in two other regions (aus and xss). However, almost 30% of Bolivia is grazable land so at least one of the two dominating biomes (savanna and tropical forest) must be on grazable land. This biome is assumed to be savanna as tropical forest is considered to be the more fertile of the two.

In summary, agricultural expansion on cultivable land in xla is assumed to affect equal shares of grassland/steppe and tropical evergreen forest (accelerated transformation) whereas expansion on grazable land is assumed to affect equal shares of savanna and dense shrubland (delayed relaxation).

USA (usa)

Utilisation trends for the two land types: The USA has full utilisation of cultivable land. The cropland area is decreasing (see **Fig. 11**) and it is likely that some of it is being converted to pastures, as this type of land use is increasing. However, the total agricultural area is slightly decreasing so the utilisation of grazable land is assumed to be falling (on the assumption that full utilisation of cultivable land is maintained).

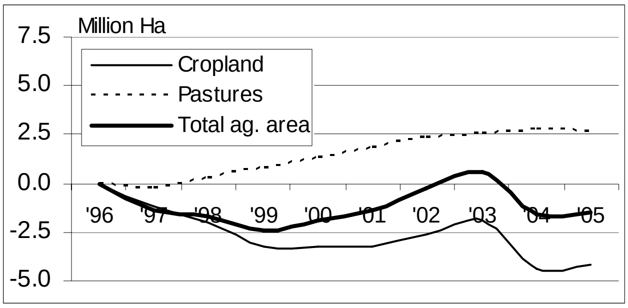


Fig. 11: Development in agricultural areas in the USA from 1996 to 2005. Reference year: 1996 [18]

Biomes affected by expansion on grazable land: According to the pasture maps (see section 2.4.2), pastures are mainly located in the Western part of the USA and it is assumed that this is also where changes in the pasture area will take place. This area is dominated by open shrubland and it is assumed that this potential vegetation type is the one affected by expansion on grazable land in the USA.

In summary, agricultural expansion on cultivable land in usa does not occur (due to full utilisation) whereas expansion on grazable land is assumed to affect open shrubland (delayed relaxation).

References

[19] Kløverpris J: Identification of biomes affected by marginal expansion of agricultural land use induced by increased crop consumption, J Clean Prod (submitted)

14 Appendix 1: The Standard GTAP Model and Database

Since the target group of this dissertation (the LCA community) is not expected to be familiar with the GTAP Model, this appendix gives a brief introduction. The description is based on Klijn and Vullings (2005) unless otherwise stated. A more in-depth mathematical description of the GTAP Model is given by Hertel (1997).

14.1 General Characteristics of the GTAP Model

The GTAP Model (together with the GTAP Database) is a representation of the global economy. It is a so-called general equilibrium (GE) model. It is general because it encompasses the entire economy (all sectors) as opposed to partial equilibrium (PE) models. It is an equilibrium model because the mathematical structure of the model ensures that supply and demand are always in balance. The results of a change in the economy can thereby be studied by implementing the given change in the model as a so-called exogenous shock. The model reacts to the new conditions by adjusting prices on goods and production factors (thereby shifting from the initial economic equilibrium to a new economic equilibrium). The output from the GTAP Model consists of all the changes (in prices, production, trade flows etc.) caused by the shock being studied. These changes are expressed in relative terms (percent). The changes caused by a shock to the model are governed by a wealth of mechanisms. The model contains an international transport sector, which ensures that transport costs are taken into account. Furthermore, the trade regulations and trade agreements are also accounted for in the simulation of changes in the economy.

The GTAP Model is a static model implying that the response to a shock occurs instantaneously. In dynamic models, the result of a change in equilibrium is given over a period of time in which the economy gradually adapts to the new conditions.

14.2 Simplified Overview of the Structure in the GTAP Regions

In the GTAP model, the world is split into regions, which all have an equal number of sectors. Fig. 19 summarises some of the main flows in a GTAP region.

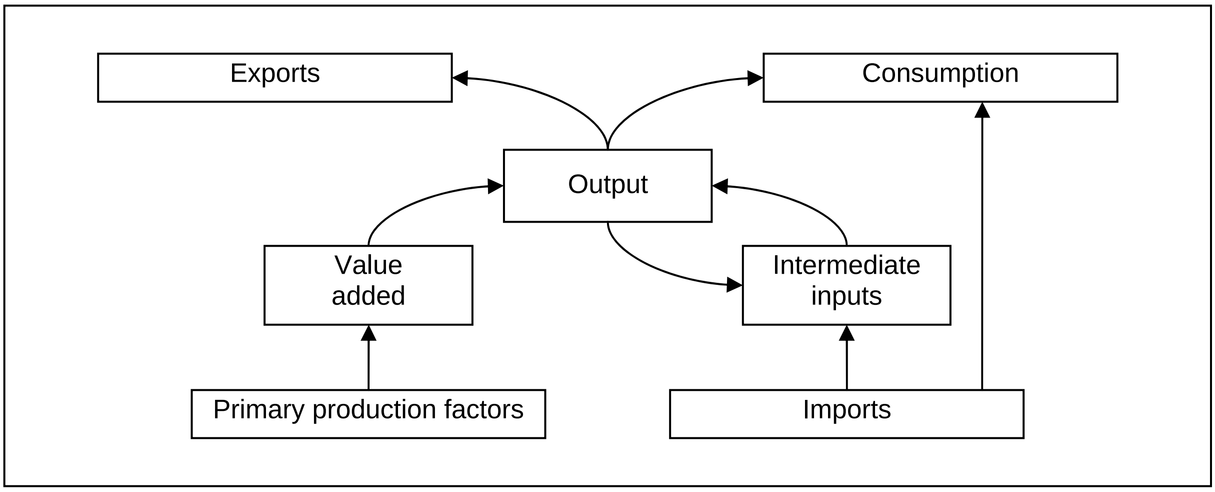


Fig. 19: Excerpt of the economy in a GTAP region. Adjusted from Klijn and Vullings (2005).

The output from the different sectors in the region is created by combining value added and intermediate inputs (composite goods). The value added comes from the primary production factors (capital, land, labour, and natural resources). The intermediate inputs may be imported from other regions and they may come from other domestic sectors. The output created by a sector may in turn be used as an intermediate input to another domestic sector. Alternatively, the output is consumed (within the region) or exported. Domestic consumption may also be satisfied by direct imports.

14.3 Production Structure in the GTAP Sectors

The GTAP Model is based on neoclassical economy and the model is programmed to ensure that the output from each sector is produced in the cheapest possible way (profit maximisation). Fig. 20 gives a more detailed overview of the production structure in a GTAP sector.

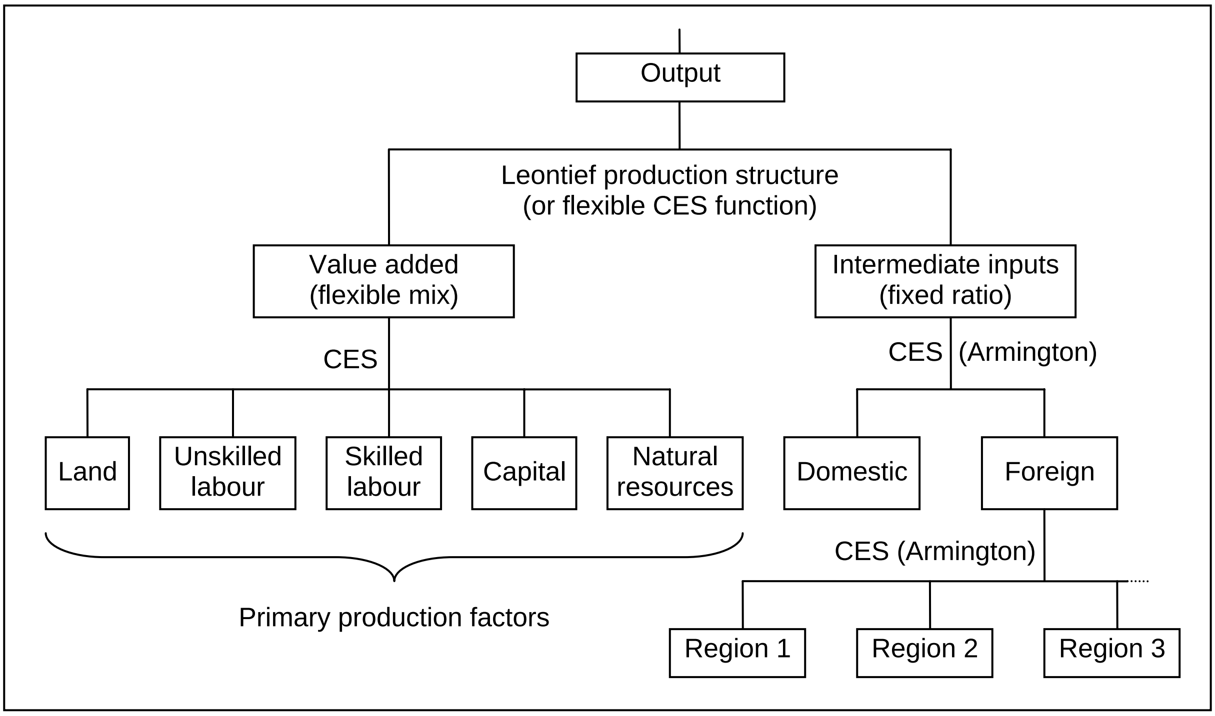


Fig. 20: Production structure in a GTAP sector. Adjusted from Klijn and Vullings (2005). The ratio between value added and intermediate inputs is either fixed (Leontief production structure) or determined by a flexible constant elasticity of substitution (CES) function. The ratio between primary production factors in the value added composite is also governed by a CES function. So is the ratio between domestic and foreign intermediate inputs and the ratio between foreign intermediate inputs from different regions but these CES functions treat products from the same sector in different regions as imperfect substitutes (the Armington approach).

A change in the supply from a given sector is determined by the supply elasticity expressing the relative change in output as a result of a relative change in the price of the output. In the GTAP Model, the supply elasticity is implicitly determined by the functions incorporated in the production structure and the remaining part of the economy. As explained above, the output from a sector is produced by combining value added and intermediate inputs (see Fig.

20). The ratio between these two composites can either be fixed (a so-called Leontief production structure) or flexible depending on the application of the model. In case the ratio is flexible, it is determined by a so-called constant elasticity of substitution (CES) function. The CES function determines the change in the ratio between inputs (in this case primary production factors) as a result of changes in the input prices. The mathematics of the CES function have not been further explored in the present dissertation. The Leontief production structure is a special case of the CES function (in which the elasticity of substitution is zero). The Leontief production structure has been applied for the ratio between value added and intermediate inputs in the land use modelling performed during the present PhD project (see Baltzer and Kløverpris 2008).

The value added composite (see Fig. 20) consists of capital, land, labour, and natural resources (primary production factors), which can substitute each other. The combination of the primary production factors is determined by the flexible CES function. Primary production factors in the GTAP Model can move from sector to sector but not from region to region.

Unlike the value added composite, the composite of intermediate inputs is characterised by a fixed ratio between the different inputs (see Fig. 20). The logic behind this can be illustrated by the following example. The production of bread requires mixing of flour, water, and yeast (intermediate inputs) in a given ratio. The ingredients cannot substitute for one another. On the other hand, the dough can be kneaded (value added) by the baker (labour) or by a kneading machine acquired by investment of capital. This illustrates how primary production factors (in this case, labour and capital) can substitute each other (depending on their prices) while intermediate inputs cannot.

As opposed to the primary production factors, intermediate inputs can be purchased both domestically and on foreign markets. The ratio between domestic and foreign inputs is determined by a CES function in which the so-called Armington approach is incorporated. This means that products from the same sector but from different regions are treated as imperfect substitutes. In other words, similar products from different regions are not considered to be exactly the same. For instance, rice from China is not considered to be the same as rice from Brazil. This is reflected by the Armington elasticities expressing the change in the ratio between domestic and foreign intermediate inputs as a result of changes in prices (the elasticity of substitution in the CES function). The Armington elasticities not only reflect actual or perceived differences between the same products from different countries. They also reflect the inertia of international trade patterns, which is caused by several factors. For instance, long-running contracts or high transaction costs may prevent buyers from shifting immediately to a cheaper supplier in response to changes in prices. This is also why the Armington elasticities are dependent on the time perspective. In the long run, the market can adjust more freely to changes and buyers can choose the cheapest suppliers. The higher the

Armington elasticities, the more flexibly the international trade patterns can adjust to price changes.

The composite of foreign intermediate inputs (see Fig. 20) is determined by yet another CES function incorporating the Armington approach. In this case, the Armington elasticity (the elasticity of substitution) expresses the change in the ratio between the intermediate inputs imported from different regions as a result of changes in prices. The Armington elasticity in this CES function is twice as high as in the CES function determining the ratio between domestic and (aggregate) foreign intermediate inputs.

The Armington elasticities also govern the ratio between consumption of domestic products and imports (see Fig. 19).

14.4 Land in the Standard GTAP Model

In the standard GTAP Model, land is normally represented as a homogeneous production factor in fixed supply (but may also be represented as a production factor in endless supply with a fixed price). Land is a so-called sluggish production factor, which means that (unlike labour and capital) it is not perfectly mobile across sectors within a region. This is a simple way of simulating the actual heterogeneity of land. Some land is better suited for one crop than another and therefore land does not necessarily move from one sector to another just because crop prices change. Unfortunately, the mathematical modelling of the sluggishness of land results in mismatch between the total change in land use and the sum of land use changes in each sector when calculated in physical units. This problem has been further discussed (and solved) by Baltzer and Kløverpris (2008).

14.5 The Standard GTAP Database

Whereas the GTAP Model consists of an analytical framework, the GTAP Database contains the information that feeds into the mathematical equations in the model. Version 6 of the database corresponds to the world economy in 2001[19]. It contains 87 regions, each with 57 sectors (including eight primary crop sectors and four primary livestock sectors). The monetary value (US$) of a wide range of economic flows is given in the database, including bilateral trade, production in all sectors, use of intermediate goods and production factors, and final consumption by governments and private households. The intersectoral linkages within regions are based on economic input-output tables (also utilised in so-called input-output LCA) and the trade flows between regions is based on international trade data. The GTAP Database also contains behavioural parameters like elasticities of substitution (e.g. the Armington elasticities) and policy instruments such as taxes, tariffs and subsidies. For further information, see Dimaranan (2006).

[19] Version 7 of the database corresponding to the world economy in 2004 was under construction at the time of writing.

15 Appendix 2: Region Aggregation

The table below shows the region aggregation in the modified version of the GTAP Database.

#	Regions in the modified database	#	Countries
1	Australia (aus)	1	Australia
2	Rest of Oceania (xoc)	2	New Zealand
		3	Cook Islands
		4	Fiji Islands
		5	French Polynesia
		6	Guam
		7	Kiribati
		8	Marshall Islands
		9	Micronesia, Fed States of
		10	Nauru
		11	New Caledonia
		12	Norfolk Islands
		13	Northern Maurina Islands
		14	Niue
		15	Palau
		16	Papua New Guinea
		17	Samoa
		18	Solomon Islands
		19	Tokelau
		20	Tonga
		21	Tuvalu
		22	Vanuatu
		23	Wallis and Futuna Is
		24	American Samoa
3	China (chn)	25	China
4	Rest of E and SE Asia (xea)	26	Indonesia
		27	Malaysia
		28	Philippines
		29	Singapore
		30	Thailand
		31	Viet Nam
		32	Korea, Republic of
		33	Hong Kong
		34	Taiwan
		35	Korea, Dem People's Rep
		36	Macau
		37	Mongolia
		38	Brunei Darussalam
		39	Cambodia
		40	Laos
		41	Myanmar
		42	Timor-Leste

#	Regions in the modified database	#	Countries
5	Japan (jpn)	43	Japan
6	Rest of S Asia (xsa)	44	Bangladesh
		45	Sri Lanka
		46	Afghanistan
		47	Maldives
		48	Nepal
		49	Pakistan
		50	Bhutan
7	India (ind)	51	India
8	Middle E and N Africa (xme)	52	Turkey
		53	Bahrain
		54	Iran, Islamic Rep of
		55	Iraq
		56	Israel
		57	Jordan
		58	Kuwait
		59	Lebanon
		60	Palestine, Occupied Tr.
		61	Oman
		62	Qatar
		63	Saudi Arabia
		64	Syrian Arab Republic
		65	United Arab Emirates
		66	Yemen
		67	Morocco
		68	Tunisia
		69	Algeria
		70	Egypt
		71	Libyan Arab Jamahiriya
9	Canada (can)	72	Canada
10	USA (usa)	73	United States of America
11	Mexico (mex)	74	Mexico
12	Rest of Cent. America (xca)	75	Belize
		76	Costa Rica
		77	El Salvador
		78	Guatemala
		79	Honduras
		80	Nicaragua
		81	Panama
		82	Antigua and Barbuda
		83	Bahamas
		84	Barbados
		85	Dominica
		86	Dominican Republic
		87	Grenada
		88	Haiti
		89	Jamaica

#	Regions in the modified database	#	Countries
		90	Puerto Rico
		91	Saint Kitts and Nevis
		92	Saint Lucia
		93	Saint Vincent/Grenadines
		94	Trinidad and Tobago
		95	Virgin Islands, US
		96	Bermuda
		97	Greenland
		98	Saint Pierre & Miquelon
		99	Anguilla
		100	Aruba
		101	British Virgin Islands
		102	Cayman Islands
		103	Cuba
		104	Guadeloupe
		105	Martinique
		106	Montserrat
		107	Netherlands Antilles
		108	Turks and Caicos
13	Peru (per)	109	Peru
14	Rest of S America (xla)	110	Argentina
		111	Bolivia
		112	Chile
		113	Colombia
		114	Ecuador
		115	Uruguay
		116	Venezuela, Bolivar Rep of
		117	Falkland Islands / Malvinas
		118	French Guiana
		119	Guyana
		120	Paraguay
		121	Suriname
15	Brazil (bra)	122	Brazil
16	Rest of EU15 (xeu15)	123	Belgium
		124	France
		125	Germany
		126	Italy
		127	Luxembourg
		128	Netherlands
		129	Ireland
		130	United Kingdom
		131	Greece
		132	Portugal
		133	Spain
		134	Austria
		135	Finland
		136	Sweden

#	Regions in the modified database	#	Countries
17	EU12 (eu12)	137	Bulgaria
		138	Cyprus
		139	Czech Republic
		140	Estonia
		141	Hungary
		142	Latvia
		143	Lithuania
		144	Malta
		145	Poland
		146	Romania
		147	Slovakia
		148	Slovenia
18	Denmark (dnk)	149	Denmark
19	Rest of Europe (xer)	150	Albania
		151	Croatia
		152	Switzerland
		153	Iceland
		154	Liechtenstein
		155	Norway
		156	Andorra
		157	Bosnia and Herzegovina
		158	Faroe Islands
		159	Gibraltar
		160	Macedonia,The Fmr Yug Rp
		161	Monaco
		162	San Marino (no dtata)
		163	Serbia and Montenegro
20	Former Soviet Union (xsu)	164	Russian Federation
		165	Armenia
		166	Azerbaijan, Republic of
		167	Belarus
		168	Georgia
		169	Kazakhstan
		170	Kyrgyzstan
		171	Moldova, Republic of
		172	Tajikistan
		173	Turkmenistan
		174	Ukraine
		175	Uzbekistan
21	South African Customs Union (xsc)	176	South Africa
		177	Botswana
		178	Lesotho
		179	Namibia
		180	Swaziland
22	Rest of Sub-Saharan Africa (xss)	181	Madagascar
		182	Malawi
		183	Mozambique

#	Regions in the modified database	#	Countries
		184	Tanzania, United Rep of
		185	Uganda
		186	Zambia
		187	Zimbabwe
		188	Angola
		189	Congo, Dem Republic of
		190	Mauritius
		191	Seychelles
		192	Benin
		193	Burkina Faso
		194	Burundi
		195	Cameroon
		196	Cape Verde
		197	Central African Republic
		198	Chad
		199	Comoros
		200	Congo, Republic of
		201	Côte d'Ivoire
		202	Djibouti
		203	Equatorial Guinea
		204	Eritrea
		205	Ethiopia
		206	Gabon
		207	Gambia
		208	Ghana
		209	Guinea
		210	Guinea-Bissau
		211	Kenya
		212	Liberia
		213	Mali
		214	Mauritania
		215	Mayotte
		216	Niger
		217	Nigeria
		218	Réunion
		219	Rwanda
		220	Saint Helena
		221	Sao Tome and Principe
		222	Senegal
		223	Sierra Leone
		224	Somalia
		225	Sudan
		226	Togo

16 Appendix 3: Sector Aggregation

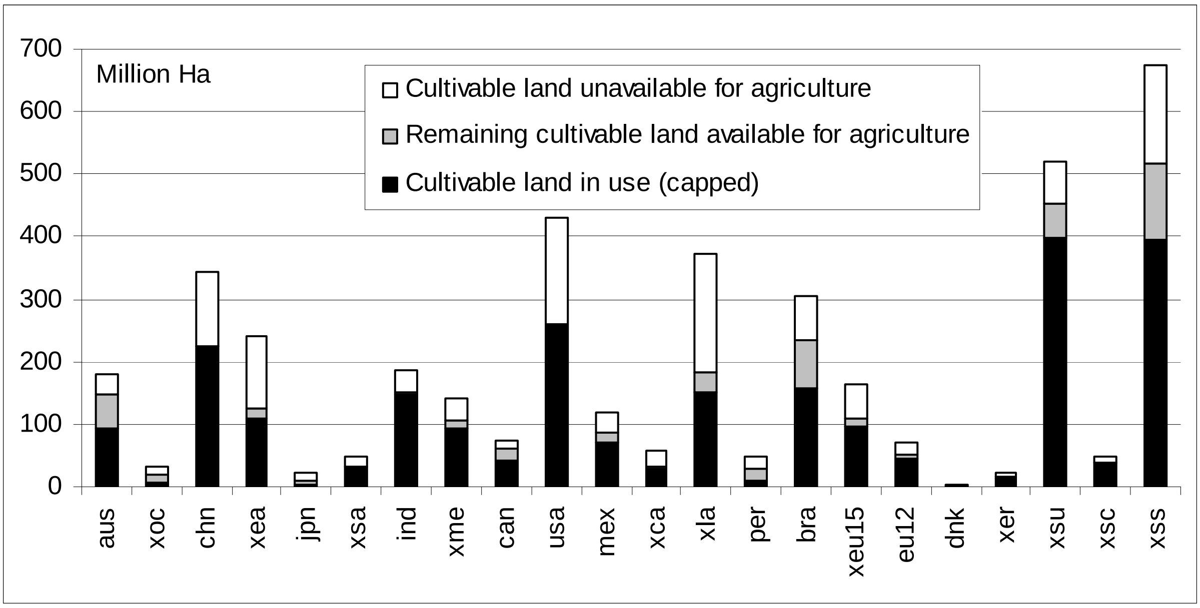
The table below shows the sector aggregation in the modified version of the GTAP Database. For a full list of the crops included in the crops sectors, see Appendix 5 (table 6 or 7).

#	Sectors the in modified database	#	Sectors in standard database database
1	Paddy rice (pdr)	1	Paddy rice
2	Wheat (wht)	2	Wheat
3	Cereal grains not elsewhere classified (gro)	3	Cereal grains not elsewhere classified
4	Vegetables, fruit, nuts (v_f)	4	Vegetables, fruit, nuts
5	Oil seeds (osd)	5	Oil seeds
6	Sugar cane, sugar beet (c_b)	6	Sugar cane, sugar beet
7	Plant-based fibers (pfb)	7	Plant-based fibers
8	Crops not elsewhere classified (ocr)	8	Crops not elsewhere classified
9	Bovine cattle, sheep and goats, horses (ctl)	9	Bovine cattle, sheep and goats, horses
10	Animal products not elsewhere classified (oap)	10	Animal products not elsewhere classified
11	Raw milk (rmk)	11	Raw milk
12	Wool and silk cocoons (wol)	12	Wool and silk cocoons
13	Food processing (food)	13	Meat: cattle, sheep, goats, horse
		14	Meat products nec
		15	Vegetable oils and fats
		16	Dairy products
		17	Processed rice
		18	Sugar
		19	Food products nec
		20	Beverages and tobacco products
14	Manufacturing (mnf)	21	Textiles
		22	Wearing apparel
		23	Leather products
		24	Wood products
		25	Paper products, publishing
		26	Petroleum, coal products
		27	Chemical,rubber,plastic prods
		28	Mineral products nec
		29	Ferrous metals
		30	Metals nec
		31	Metal products
		32	Motor vehicles and parts
		33	Transport equipment nec
		34	Electronic equipment
		35	Machinery and equipment nec
		36	Manufactures nec
		37	Forestry
		38	Fishing
		39	Coal
		40	Oil
		41	Gas

#	Sectors the in modified database	#	Sectors in standard database database
		42	Minerals nec
15	Services (svc)	43	Electricity
		44	Gas manufacture, distribution
		45	Water
		46	Construction
		47	Trade
		48	Transport nec
		49	Sea transport
		50	Air transport
		51	Communication
		52	Financial services nec
		53	Insurance
		54	Business services nec
		55	Recreation and other services
		56	PubAdmin/Defence/Health/Educat
		57	Dwellings

17 Appendix 4: Adjustment of Cultivable Land

This appendix shows the adjustment of the cultivable land estimates made by Ramankutty et al. (2002b). Furthermore, the appendix shows the areas of cultivable land considered available for future agricultural expansion and, finally, the cultivable land currently in use is shown (capped at the estimated availability for agriculture).



18 Appendix 5: Calculation Explanation

This appendix describes the calculations performed in the present PhD project. The spreadsheet is available on the enclosed CD (Appendix 6).

There are eight different worksheets in the spreadsheet. The first three sheets are data sheets. The next four sheets are result sheets for the different scenarios (increased wheat consumption in four different countries), and the last sheet collects the main results from the scenario sheets. Each worksheet will be described independently below.

All tables referred to in this appendix are tables in the spreadsheet.

18.1 Land Utilisation Sheet (UTIL)

The first worksheet (UTIL) shows how the utilisation of cultivable and grazable land has been calculated. Table 1 simply aggregates the main results for the 22 GTAP regions. Table 2 contains the stepwise calculation of the utilisation of cultivable and grazable land. As part of these calculations, the areas of crops and pastures on cultivable land and pastures on grazable land are also calculated. The following sections will briefly describe the different columns in Table 2.

18.1.1 Unadjusted Land Data (B-G)

The unadjusted land data shown in blue in column B to G was kindly provided by Navin Ramankutty (McGill University, Montreal, Canada), who did an overlay of cultivable land and agricultural areas (cropland and pastures). The data includes –

B: Total land area
C: Cultivable land (unadjusted)
D: Cropland area in 2000
E: Pasture area in 2000
F: Cultivable land (unadjusted) excl. crops on cultivable land
F: Cultivable land (unadjusted) excl. crops and pastures on cultivable land

18.1.2 Potentially Grazable Land Unadjusted (H)

As a starting point, all land which is not cultivable is considered potentially grazable land, i.e. land which is not fertile enough for crop cultivation but good enough to be used as pastures. The potentially grazable land is obtained by subtracting the unadjusted area of cultivable land (column C) from the total land area (column B).

18.1.3 Fractions of Total Land Area Unavailable for Agriculture (I-M)

Column I to M contains data on the fractions of the total land area that is not available for agricultural production. The areas not considered available for agricultural production include:

I: Deserts
J: Areas steeper than 30%
K: Protected areas
L: Human settlements on cultivable land
M: Human settlements on grazable land

The establishment of the data in column I to M has been explained by Baltzer and Kløverpris (2008).

18.1.4 Land Available for Agriculture (N-Q)

Column O and P list the fractions of respectively cultivable and grazable land available for agricultural production. The calculation of these fractions is based on the following assumptions:

1. Desert is only found on potentially grazable land (unadjusted).
2. Steep and protected areas are proportionately distributed across land types.
3. Deserts, steep areas, and protected areas are overlapping so if 10% of the entire land area is protected, so is 10% of the deserts and 10% of the steep areas. This is conceptually illustrated in Article 2 (Kløverpris et al. 2008b, Fig. 2).
4. Human settlements are not overlapping with deserts and steep and protected areas.

Column P and Q list the area of cultivable and grazable land available for agricultural use.

18.1.5 Unavailable and Unused Cultivable Land (R-S)

Column R lists the cultivable land unavailable for agricultural production and column S lists the cultivable land, which is available for agricultural production but not being utilised.

18.1.6 Crops on Cultivable Land (T-U)

Column T lists the area of cultivable land covered by cropland. It is calculated by subtracting the unadjusted area of cultivable land excl. crops on cultivable land (column F) from the total unadjusted area of cultivable land (column C). Because the unadjusted area of cultivable land is used in the calculation, the area of crops on cultivable land (column T) may in some cases exceed the area of cultivable land available for agriculture (column N). Therefore, the fraction of available cultivable land covered by crops (column U) may in some cases exceed 100%. This is due to the inherent uncertainties in the estimation of the area of cultivable land available for agriculture.

18.1.7 Crops on Cultivable Land Exceeding the Availability (V)

If the area of crops on cultivable land (column T) exceeds the area of cultivable land available for agriculture (column P), the surplus is listed in column V.

18.1.8 Pastures on Cultivable and Grazable Land (W-Z)

The area of pastures on cultivable land is listed in column Y. To obtain this area, the available area of cultivable land not covered by crops is calculated in column W by subtracting crops on cultivable land (column T) from cultivable land available for agriculture (column P). Furthermore, the unadjusted area of pastures on cultivable land (column X) is calculated based on the overlay data in column F and G. If the available area of cultivable land is fully utilised (indicated by a zero in column V), pastures on cultivable land (column Y) is determined by the available cultivable land excl. crops on cultivable land (column W). Otherwise, the unadjusted area of pastures on cultivable land (column X) makes up the area of pastures on cultivable land (column Y).

The area of pastures on grazable land (column Z) is simply calculated by subtracting the area of pastures on cultivable land (column Y) from the total pasture area in 2000 (column E). The area of pastures on grazable land (column Z) may in some cases exceed the area of grazable land available for agriculture (column Q). This is accounted for in the calculation of the utilisation of grazable land (column AD).

18.1.9 Cultivable and Grazable Land in Use (AA-AB)

The area of 'cultivable land in use' (column AA) is calculated by adding together crops and pastures on cultivable land (column T and Y). Due to uncertainties in the estimation of land available for agricultural use, the sum of crops and pastures on cultivable land sometimes exceeds the cultivable land available (column P). In those cases, the 'cultivable land in use' is capped at the limit of availability in order not to reach utilisation levels above 100%.

The area of 'grazable land in use' (column AB) is calculated by adding together 'pastures on grazable land' (column Z) and 'crops on cultivable land exceeding available cultivable land' (column V). Just as for cultivable land, the area of 'grazable land in use' is capped at the limit of availability (column Q) in order not to reach utilisation levels above 100%.

Crops on cultivable land exceeding available cultivable land (column V) has been included in the calculation of 'grazable land in use' (column AB) to account for the full area of crops on cultivable land as reported by Navin Ramankutty (see Section 18.1.1). What has not been included in the calculation is the area of crops grown on grazable land, i.e. the difference between the cropland area (column D) and crops on cultivable land. The reason is that with the land use definitions applied in the study, grazable land is not suitable for crop production. However, this relies on soil and climate conditions, including precipitation levels. With artificial irrigation, it is possible to change these conditions and thereby make grazable land suitable for crop production. This is done in many countries and therefore the algorithm applied to calculate the utilisation of grazable land (see above) underestimates the actual utilisation. For most countries, the error is very small but for some countries, especially in Asia, the underestimation is substantial. India's utilisation of grazable land is estimated at 6% but, in fact, it is more likely to be 48%. Seen in retrospect, crops on grazable land should have been included in the calculation of the utilisation of grazable land. This would have lead to less expansion on grazable land in the GTAP modelling of increased wheat consumption. Meanwhile, the expansion on grazable land only constitutes a minor share of the total expansion (see Fig. 13) so the underestimation of grazable land in use does not seem to have a significant influence on the final results.

18.1.10 Utilisation of Cultivable and Grazable Land (AC-AD)

The utilisation of cultivable land (column AC) is calculated by dividing cultivable land in use (column AA) with the area of available cultivable land (column P). Likewise, the utilisation of grazable land (column AD) is calculated by dividing grazable land in use (column AB) with the area of available grazable land (column Q).

18.1.11 Alternative Estimation of Grazable Land Utilisation (AE-AH)

The four columns from AE to AH have been used to assess the significance of the choices made in the calculation of grazable land in use (see the discussion in Section 18.1.9).

18.2 Agricultural Statistics from the FAOSTAT Database (FAO)

The second worksheet (FAO) contains data on production of crops and livestock as well as harvested areas of crops. This data is retrieved from FAOSTAT (2007). All data is for the year 2001. It is thereby compatible with the GTAP Database applied in the study (reflecting the world economy in 2001).

Table 3 contains aggregated production data for all land dependent sectors (eight crop sectors and two livestock sectors) in the 22 GTAP regions. Table 4 contains the corresponding information for the area harvested in each crop sector. Table 5 contains the fraction of the total area harvested made up by each crop sector in each region. This is the information applied to distribute the total area of crops on cultivable land in a region among the eight crop sectors.

Table 6 and 7 contain the raw FAOSTAT data on crop production and area harvested, respectively. The data covers more than 200 countries and approximately 150 different crops. The data has been manually sorted in crop sectors and regions.

Table 8 contains the raw FAOSTAT data on production of cattle meat and milk. This has also been manually sorted in the 22 GTAP regions.

18.3 Base Data for the Conversion of the GTAP Output (BASE)

The third worksheet (BASE) contains the data applied in the conversion of the GTAP output in the different scenarios.

18.3.1 Cropland and Pastures on the Two Land Types (Table 9)

Table 9 contains the cropland areas in the 22 GTAP regions. According to the definitions applied in the modelling, crops can only grow on cultivable land (see Section 4.1.1). The cropland area is therefore defined as the area of crops on cultivable land (UTIL row 6) even though the actual cropland area in some cases is larger than this (mainly due to cultivation on irrigated grazable land). The worst mismatch is found in the region called Rest of South Asia (xsa) where the actual cropland area is almost 80 percent higher than the cropland area on cultivable land. In Peru and Denmark, the same figure is respectively 30 and 37 percent. In Australia, India, the Middle East and North Africa, Canada, the South African Customs Union, and Sub-Saharan Africa the actual cropland area is between 19 and 27 percent higher than the cropland area on cultivable land and, for the remaining 13 regions, the problem is less outspoken (see Fig. 21).

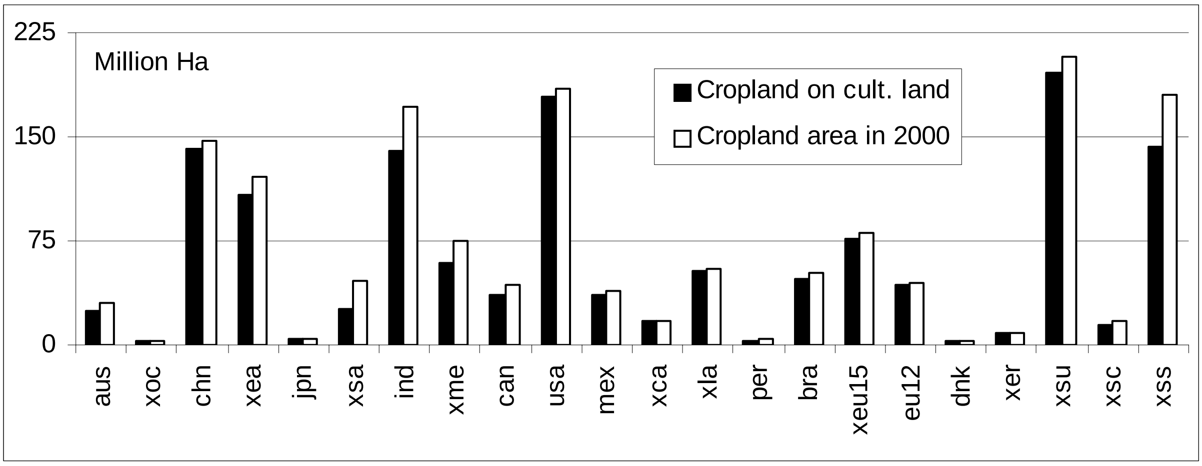


Fig. 21: Comparison of cropland on cultivable land (unadjusted overlay data) and cropland area in 2000 (based on Ramankutty et al. 2007) in the 22 GTAP regions

The discrepancy between 'cropland on cultivable land' and 'cropland area in 2000' affects the redistribution of land value in the modified GTAP Database (see Section 4.1.4) and thereby the results of the modelling. The influence of using 'cropland area in 2000' to estimate the total area of cultivable land in the crop sectors (A_{crop}) is investigated in the sensitivity analyses.

18.3.2 Area of Cultivable Land in the Agricultural Sectors (Table 10)

In table 10, cropland and pastures on cultivable land (table 9) are distributed among the agricultural sectors. This operation is split in two: First, cropland on cultivable land is distributed among the crop sectors, and then pastures on cultivable land are distributed among the livestock sectors. This is illustrated in Fig. 7 and the details are explained below.

Cropland on cultivable land is distributed among the eight crop sectors assuming that this distribution is similar to the distribution of area harvested. This is done by multiplying the total area of cropland (on cultivable land) with the fractions of area harvested (table 5 in the FAO worksheet).

Pastures on cultivable land are distributed among the livestock sectors by use of value weights from the GTAP database (calculation not included in the spread sheet). This means that if the value of production in the raw milk sector is two-thirds of the total value of production in the land dependent livestock sectors, two-thirds of the pastures on cultivable land is assigned to the raw milk sector. Wool (wol) and animal products not elsewhere classified (oap) are assumed not to use land at all. Items 13-17 in table 10 have been included for practical reasons as this eases the transfer of data from the GTAP (HAR) files to the spread sheet.

The total area of cropland and pastures on cultivable land is given in the lower part of table 10. Finally, the cultivable land used by the non-wheat crop sectors is calculated at the bottom of the table.

18.3.3 Area of Grazable Land in the Agricultural Sectors (Table 11)

In table 11, ‘pastures on grazable land’ are distributed among the two land dependent livestock sectors, cattle and raw milk. Again, the distribution is based on value weights from the GTAP database (see previous section) and the calculation is not included in the spread sheet, only the results of the calculation.

18.3.4 Production and Average Crop Yields (Table 12 and 13)

Table 12 lists the production data from the worksheet FAO. In table 13, the average yields for the eight crop sectors in the different regions are calculated by dividing the production data in table 12 with the cropland areas on cultivable land in table 10. As mentioned in Section 18.3.1, the actual cropland areas are, in some regions, larger than the area of cropland on cultivable land (due to irrigation). This means that the production listed in table 12 is actually produced on a larger area than that listed in table 10. The yields in table 13 might therefore be somewhat overstated, especially for the region called South East Asia (xsa).

To get an impression of the error on the calculated yields in table 13, the yields are compared with those reported by FAOSTAT (2007). This yield is simply the production divided by the area harvested (table 14). It is important to be aware that the FAOSTAT yield is not directly comparable to the calculated yields in table 13. The reason is that the FAOSTAT yield is calculated on the basis of the harvested area (not the cropland area). As some areas may be harvested more than once a year (especially in the tropics), the harvested area in a given year may be larger than the actual area of cropland. On the other hand, cropland may include fallow land, which is not being harvested. Due to these aspects, the denominator in the two alternative calculations of crop yields (table 13 and 14) is not the same so, even if data was perfectly compatible, different results would be obtained. However, the yield comparison is performed to get an indication of the error in table 13. The deviation between the two yield calculations is listed in table 15.

Interestingly, the calculated yields in table 13 are significantly lower than the FAOSTAT yields (table 14) for the following regions: Rest of Oceania, USA, Mexico, Rest of Central America, Rest of Former Soviet Union, and South African Customs Union. These regions (except the last one) all have no or only minor deviations between the 'cropland area in 2000' and the area of 'cropland on cultivable land' (see table 1). This implies that cropland on cultivable land (used to indicate the cropland area in the yield calculation in table 13) is larger than the area harvested in the relevant regions. There may be several reasons for this, including a low cropping intensity, large areas of fallow land, and an overestimation of the actual cropland area.

For the following regions, the calculated yields in table 13 are larger than the FAOSTAT yields in table 14: China, Rest of South Asia, India, Middle East and North Africa, Brazil, and Rest of Sub-Saharan Africa. Not surprisingly, this is mostly outspoken for Rest of South Asia (xsa), which has an actual cropland area that is significantly higher than the area of cropland on cultivable land (see Section 18.3.1).

18.4 Scenario Worksheets (BXX, CXX, DXX, UXX)

Worksheet 4 to 7 contains the conversion of the GTAP output for simulation of increased wheat demand in respectively Brazil, China, Denmark, and the USA. The first letter in the title of each worksheet represents the scenario country, e.g. B for Brazil. The next letters indicates the type of scenario:

CO: Core scenario
TD: Technological development scenario
DA: Double Armington scenario
QA: Quadruple Armington scenario

As the four worksheets have the same structure, one general description will be given to cover all of them.

18.4.1 Output from the GTAP Model (Table 16-18)

The first three tables contain the output from the GTAP Model pasted directly into the spread sheet. All numbers express relative changes in percent. Table 16 lists the change in production in all sectors of the economy caused by the change in wheat demand. Table 17 and 18 lists the change in use of cultivable and grazable land, respectively. The three tables also contain some figures, which are not of relevance. These have been included for practical reasons as this eases the transfer of data from the GTAP solution files (SOL) to the spread sheet.

18.4.2 Change in Land Type Utilisation (Table 19 and 23)

Table 19 and 20 list the calculated expansion on cultivable and grazable land (in total). The calculations are based on the GTAP output in table 16 and the areas of cropland and pastures on respectively cultivable and grazable land (the totals in table 10 and 11).

Table 21 lists the calculated change in the use of cultivable land in each sector of the 22 regions. The calculations are based on the GTAP output in table 17 and the area of cultivable land in each crop sector (table 10). Table 21 also lists the area of non-wheat crops displaced by wheat. This is done by subtracting the entire change in crop areas (all eight crop sectors) from the change in wheat area (resulting in a negative area indicating a decline in the area cultivated with non-wheat crops). However, this calculation only makes sense if the wheat area is the only crop area that increases. This is always the case for the scenario country, i.e. the country in which the modelled increase in wheat demand is placed. In the US scenario, a meaningful displacement of non-wheat crops can also be calculated for Canada. The sum in table 21 should, in principle, add up to the listed expansion on cultivable land in table 20. In a few cases, there are minor deviations, which simply occur due to rounding in the GTAP output in table 16 and 17.

Table 22 lists the calculated change in the use of grazable land in the two land dependent livestock sectors of the 22 regions. The sum in table 22 should, in principle, add up to the listed expansion on grazable land in table 20. Again, minor deviations occur due to rounding in the GTAP output (table 16 and 18).

Table 23 lists the expansion split on agricultural land uses, i.e. the change in cropland and pastures.

18.4.3 Change in Production (Table 24-26)

Table 24 contains the calculated change in production in the crop sectors. This is calculated by multiplying the change in production (GTAP output in table 16) and the production data (table 12).

Table 25 contains the calculated change in production in the crop sectors caused by change in area. The change is calculated by multiplying the calculated crop yield (table 13) with the calculated change in the use of cultivable land in the crop sectors (table 21). In principle, this calculation could simply have been performed by multiplying the production in the crop sectors (table 12) with the change in the use of cultivable land in the crop sectors (GTAP output in table 17). The reason is that the influence of the area is cancelled in the calculation ($\Delta Q_{A,c} = \Delta A_{u,cult,c} \cdot Y_c = q_{lnd,cult,c} \cdot A_{u,cult,c} \cdot Q_c \,/\, A_{u,cult,c} = q_{lnd,cult,c} \cdot Q_c$). This shows why the calculation of the change in production caused by change in area is not affected by the estimation of the initial area of cropland (see Section 18.3.1). However, as the initial area of cropland enters into the modified version of the GTAP database (distributed among the eight crop sectors), the GTAP output describing the relative change in use of cultivable land ($q_{lnd,cult,c}$) may be indirectly affected.

Table 26 contains the calculated change in production in the crop sectors caused by the demand driven change in intensity. This change is simply calculated by subtracting the change in production caused by change in area (table 24) from the total change in production (table 25).

18.4.4 Change in Crop Yields (Table 27-28)

In table 27 and 28, the absolute and the relative changes in crop yields are calculated. These calculations are used as an assessment of the intensification level. The calculations are directly influenced by the estimation of the cropland area in each crop sector (table 10). As these areas may be underestimated in some cases (see Section 18.3.1), some of the relative changes in yield may be overestimated (because the intensification occurs on a larger area than the one used in the calculations). The changes in crop yields should therefore be seen as an upper estimate.

18.4.5 Overall Changes (Table 29)

Table 29 lists the modelled change in household wheat demand and the resulting increase in household wheat consumption in the households of the scenario country. The latter is based on the GTAP output (calculation not shown in spread sheet). Furthermore, the table lists the global change in wheat production as a result of the change in wheat demand. This is supplemented with a calculation of the net change in production, i.e. the total change minus the increase in the wheat sectors own consumption of wheat (seeds). The wheat sectors own consumption of wheat is given at the bottom of table 29. This number is also calculated based on the GTAP output (calculation not shown in spread sheet). Finally, table 29 lists the global change in production of non-wheat crops (table 24).

18.4.6 Most Significant Changes in Wheat Production (Table 30)

Table 30 lists the regions with the most significant changes in wheat production. These regions have been picked manually and are thereby not selected automatically by the spread sheet. In the upper part of table 30, the changes in the wheat area are listed. For the scenario country (and for Canada in the US scenario), the change in wheat area is divided into displacement of other crops, displacement of livestock, and expansion on cultivable land (new land taken into production). Displacement of other crops is given in table 21 and the expansion is given in table 20. The displacement of livestock is calculated (in table 30) by subtracting expansion on cultivable land (area in table 20) and displacement of other crops (area in table 21) from the overall change in wheat area in the relevant region (also given in table 21).

In the lower part of table 30, the changes in wheat production for the selected regions are listed. For the scenario country (and for Canada in the US scenario), the production changes are divided into displacement of other crops, displacement of livestock, and expansion (corresponding to the areas given in the upper part of the table). In the conversion of the GTAP output, the estimation of the overall changes in wheat production is independent of the yield estimation. However, this is not the case for the distribution of the wheat production among the different production categories in table 30. As mentioned previously, the change in production caused by change in area in a given crop sector (table 25) can be calculated independently of the yield. If this is done, the change in wheat production caused by displacement of other crops and livestock becomes independent of the yield. The reason is that the production derived from displacement is then calculated as the total production change ($\Delta Q_{wht,r}$) multiplied by the ratio between area of displacement (the absolute value of $\Delta A_{C,r}$ and $\Delta A_{L,r}$, respectively) and the change in wheat area ($\Delta A_{u,cult,wht,r}$). Both of these areas (the numerator and the denominator in the ratio) are calculated as a fraction of the total crop area, which thereby cancels out. If the calculation is not dependent on the crop area, neither is it dependent on the crop yield.

This is somewhat different for the calculation of the wheat production derived from expansion. This is simply calculated by multiplying the area of expansion (on cultivable land) with the yield. As long as the yield is consistently determined based on the cropland area on cultivable land (table 9), the sum of the different production categories in table 30 add up to the total production change listed in table 24. Using the same notation as in Article 2 (Kløverpris et al. 2008b), the wheat production caused by expansion in the scenario country can be written as follows:

$$\Delta Q_{E,wht} = \Delta A_{u,cult} \cdot Y_{wht} = A_{u,cult} \cdot q_{o,cult} \cdot \frac{Q_{wht}}{\frac{H_{wht}}{H_{tot}} \cdot A_{crop}}$$

The important thing to notice in the equation above is that A_{crop} is a fraction of $A_{u,cult}$, which is why the two areas do not cancel out. A_{crop} could also be written as $A_{u,cult} - A_{past,cult}$ (where $A_{lvstk,cult}$ is the area of cultivable land used as pastures).

18.4.7 Change in Production of Livestock (Table 31)

Table 31 lists the changes in livestock production given per tonne of increased wheat consumption in the households of the scenario country. The calculation is based on the production of livestock in table 12 (BASE), the GTAP output in table 16, and the change in household wheat consumption given in table 29.

18.5 Joint Presentation of Results (ALL)

The last worksheet basically selects all of the results from the scenario sheets and presents them per tonne of increased household wheat consumption in the scenario countries. As most of the underlying calculations have already been discussed above, the description of this worksheet will be brief (and the reader may choose to go directly to Section 18.5.4). Unnumbered tables are not discussed.

18.5.1 Expansion of the Agricultural Area (table 32-37)

Table 32 lists all the expansion results from table 20. Table 33 lists the regions accounting for at least 90% of the total expansion in each scenario (manually ranked according to magnitude of contribution). Table 34 lists the same data as table 33, only given per tonne of increased household consumption in the scenario country. Table 35 lists the fraction of total expansion contributed by each region. Table 36 and 37 list the distribution of expansion between the two land types in each region.

18.5.2 Changes in Wheat Production (table 38-40)

Table 38 lists the changes in wheat production calculated in table 30. Table 39 lists the same data as table 38, only as the fractions of increased wheat production contributing to the total change in wheat production. Table 40 lists the same data as table 38, only given per tonne of increased household consumption in the scenario country.

18.5.3 Changes in Production of Non-wheat Crops (table 41-45)

Table 41 lists the change in production of non-wheat crops caused by respectively change in area (table 25) and change in intensity (table 26). Table 42 lists the same data given for the regions with the largest changes in wheat production. Table 43 lists the same data, only given per tonne of increased household consumption in the scenario country. Table 44 lists the same data as table 42, only with opposite signs for production from change in area and total (preparation for graphic illustration). Table 45 lists the same data as table 44, only given per tonne of increased household consumption in the scenario country.

18.5.4 Biomes affected by Agricultural Expansion (table 46-48)

Table 46 lists the results from the biome analysis, i.e. the types of potential vegetation assumed to be affected by expansion on the two land types (Article 3: Kløverpris 2008). Based on these results and table 34 (net expansion per tonne of wheat consumed in households), the areas of biomes affected by agricultural expansion due to consumption of one tonne of wheat are listed in table 47. Furthermore, table 48 lists the production changes caused by change in area and intensity for respectively wheat and non-wheat crops. Finally, table 48 demonstrates how the land use results (in this case for the Brazilian scenario) can be split between accelerated transformation and delayed relaxation on respectively cultivable and grazable land. This allows for a more detailed life cycle impact assessment (LCIA) of the land use changes induced by wheat consumption.

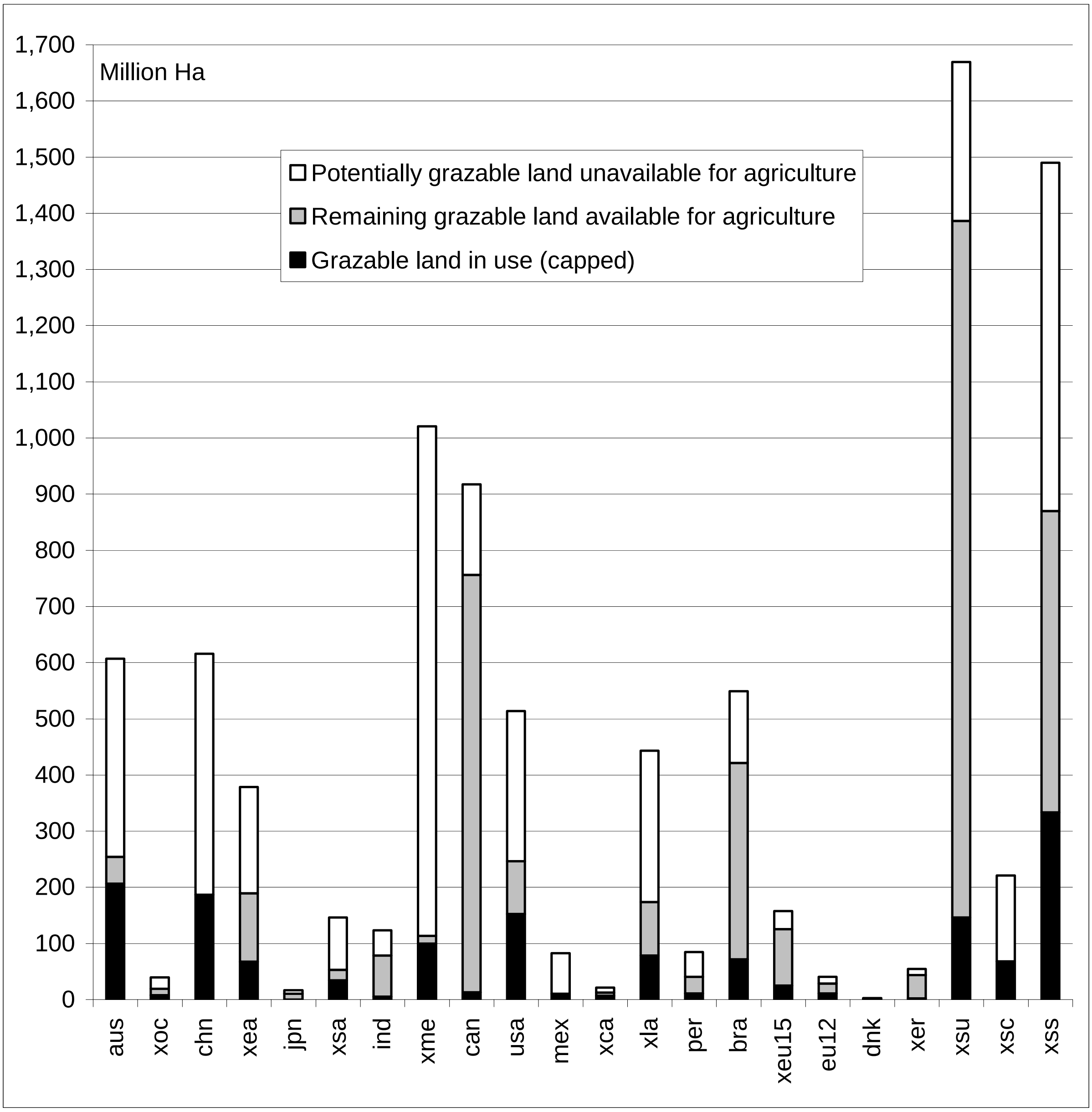
19 Appendix 6: Calculation Spreadsheet

This appendix (enclosed CD) contains 6 versions of the calculation spreadsheet:

- Appendix 6a – core scenarios
- Appendix 6b – Double Demand scenarios
- Appendix 6c – Technological Development scenarios
- Appendix 6d – Double Armington scenarios
- Appendix 6e – Quadruple Armington scenarios
- Appendix 6f – Alternative cropland area

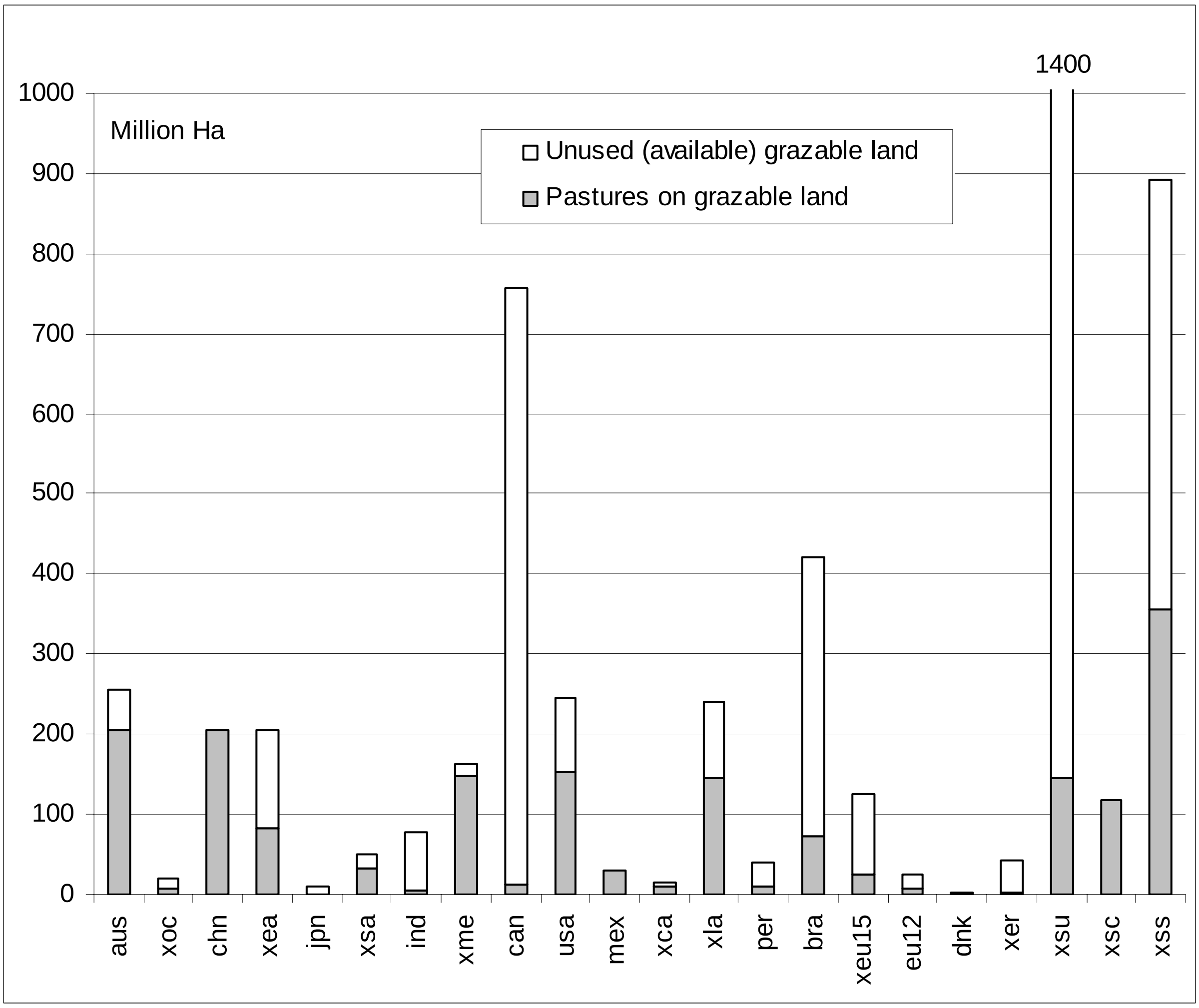
20 Appendix 7: Adjustment of Potentially Grazable Land

This appendix shows the adjustment of the potentially grazable land. Furthermore, the appendix shows the areas of pastures on grazable land. The graph does not show the areas of (irrigated) cropland on grazable land as these have been disregarded in the modelling, which means that the area of unused grazable land is somewhat overestimated. See discussion in Appendix 5.

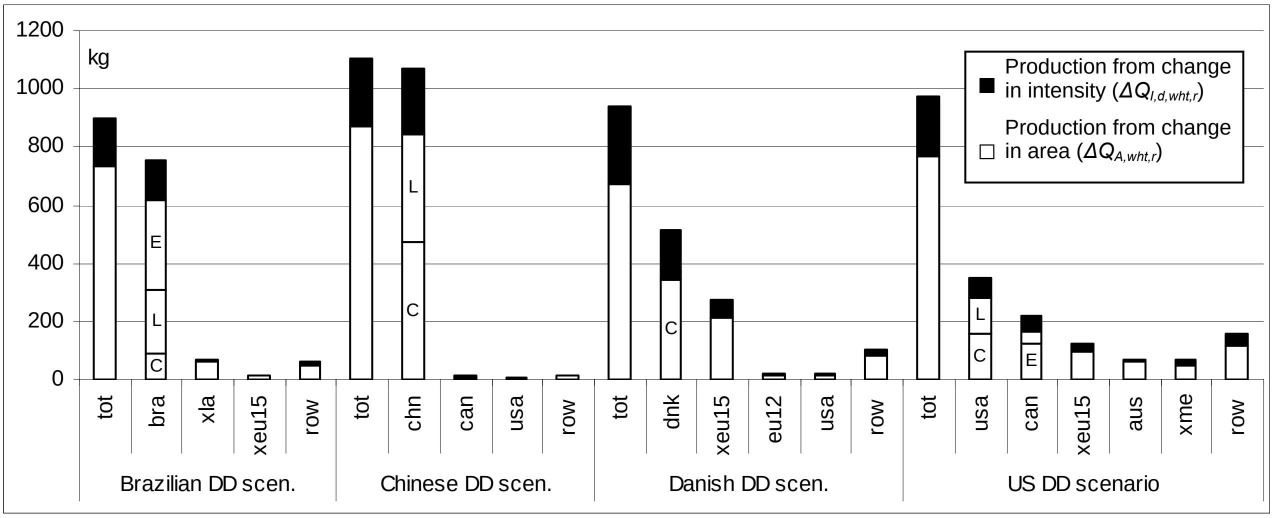


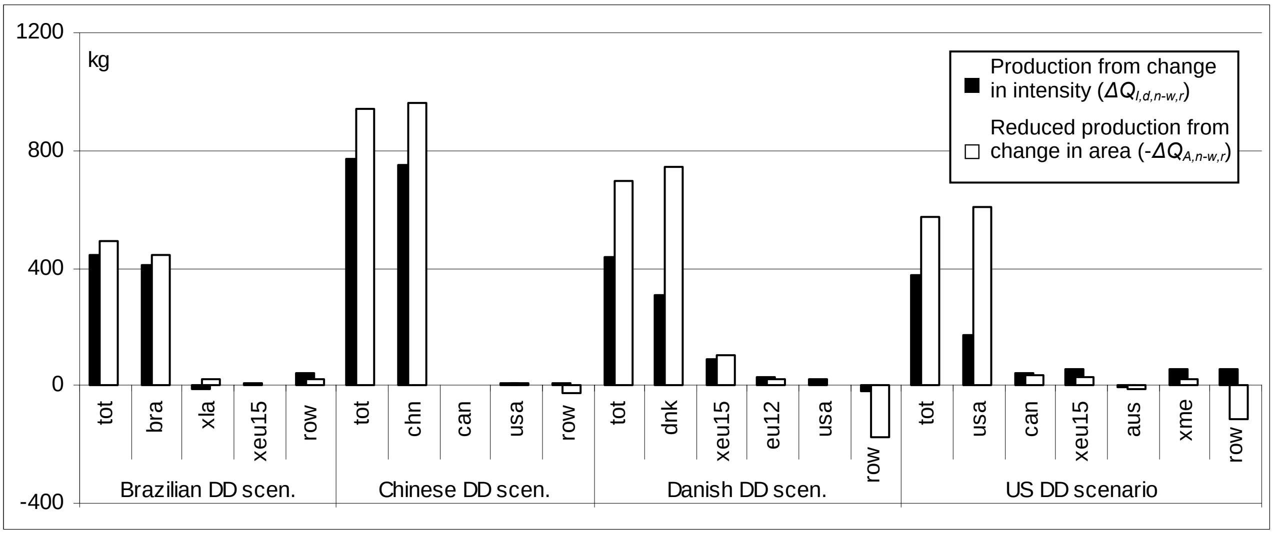
21 Appendix 8: Grazable Land Available for Agricultural Production

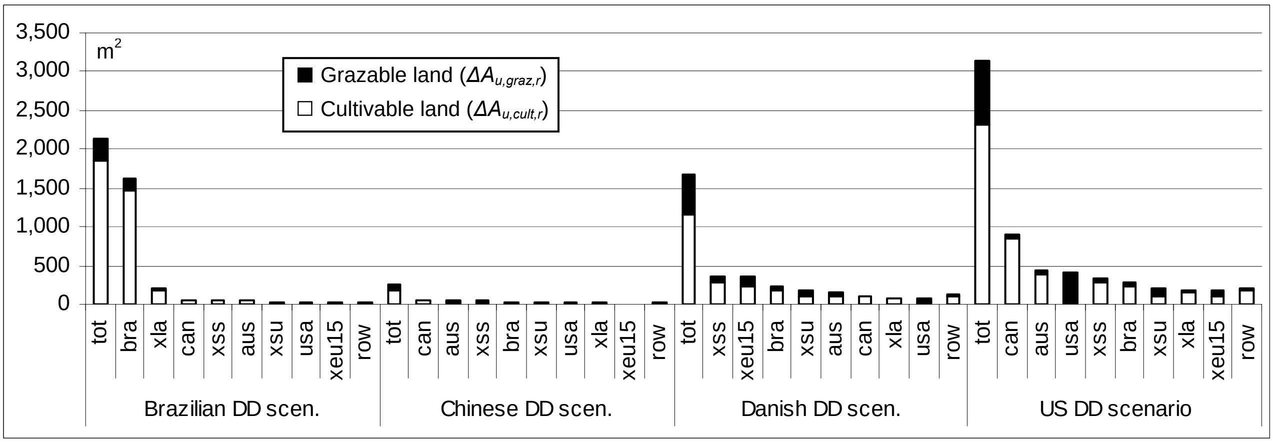
This appendix shows the areas of pastures on grazable land that is distributed among the land dependent livestock sectors in the modified GTAP Database. The graph does not show the areas of (irrigated) cropland on grazable land as these have been disregarded in the modelling, which means that the area of unused grazable land is somewhat overestimated. See discussion in Appendix 5.



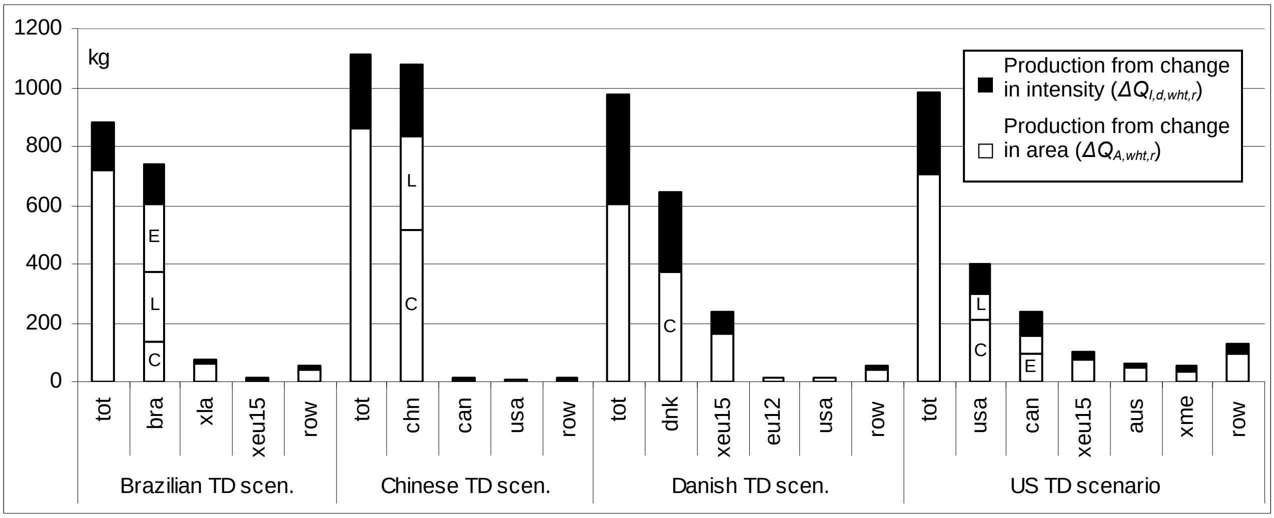
22 Appendix 9: Double Demand (DD) Scenarios

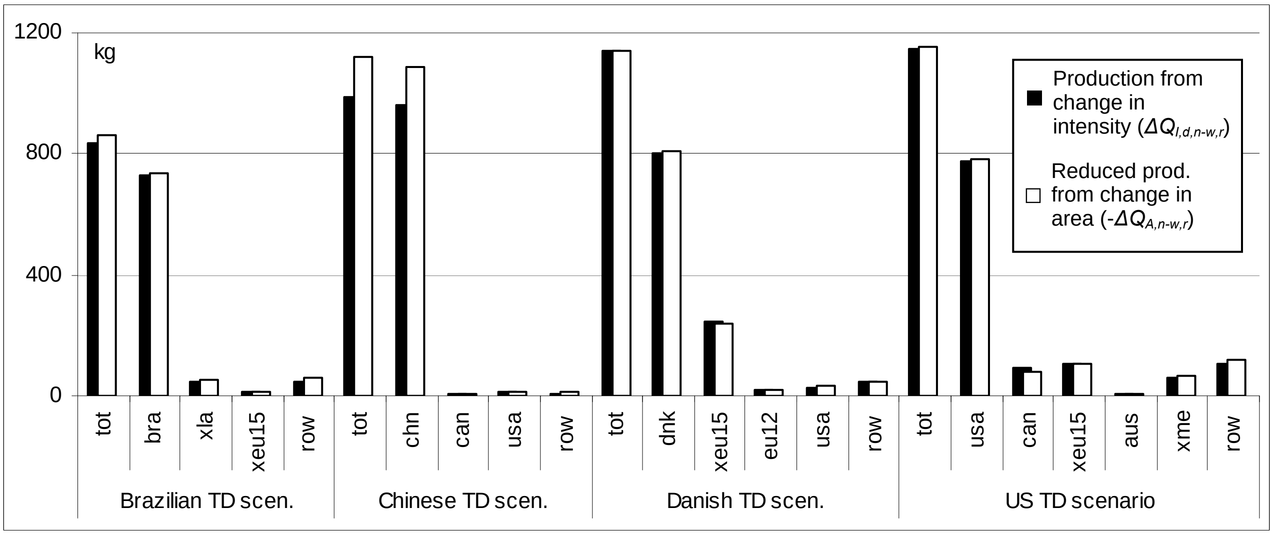


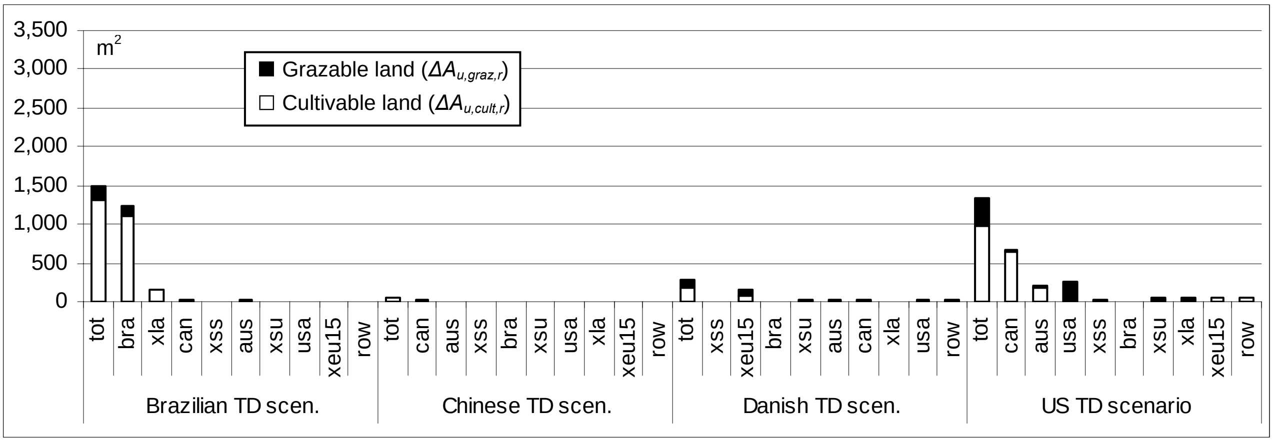




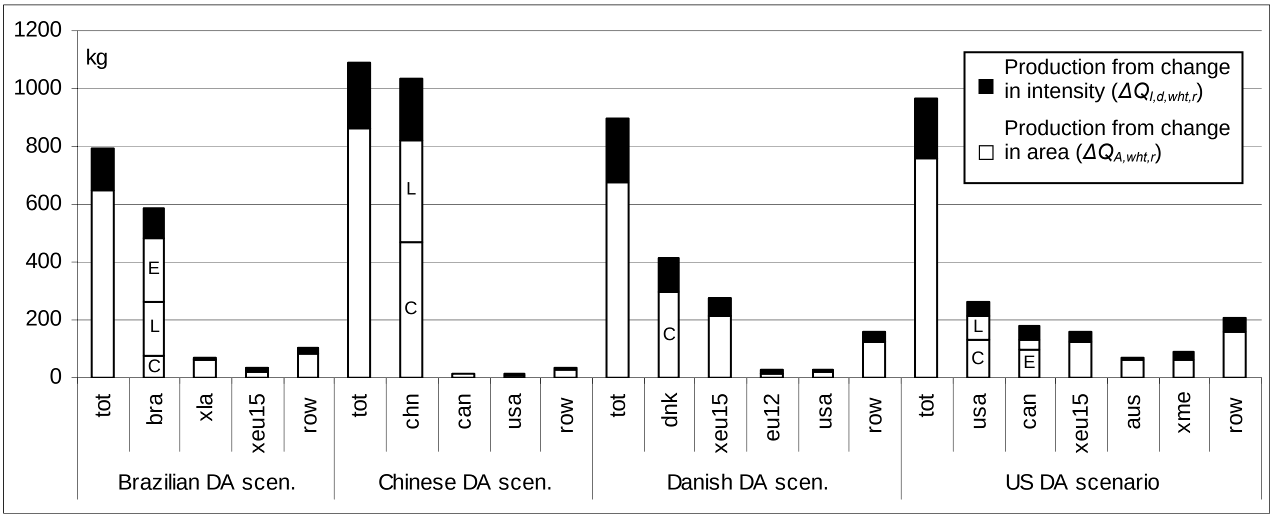
23 Appendix 10: Technological Development (TD) Scenarios

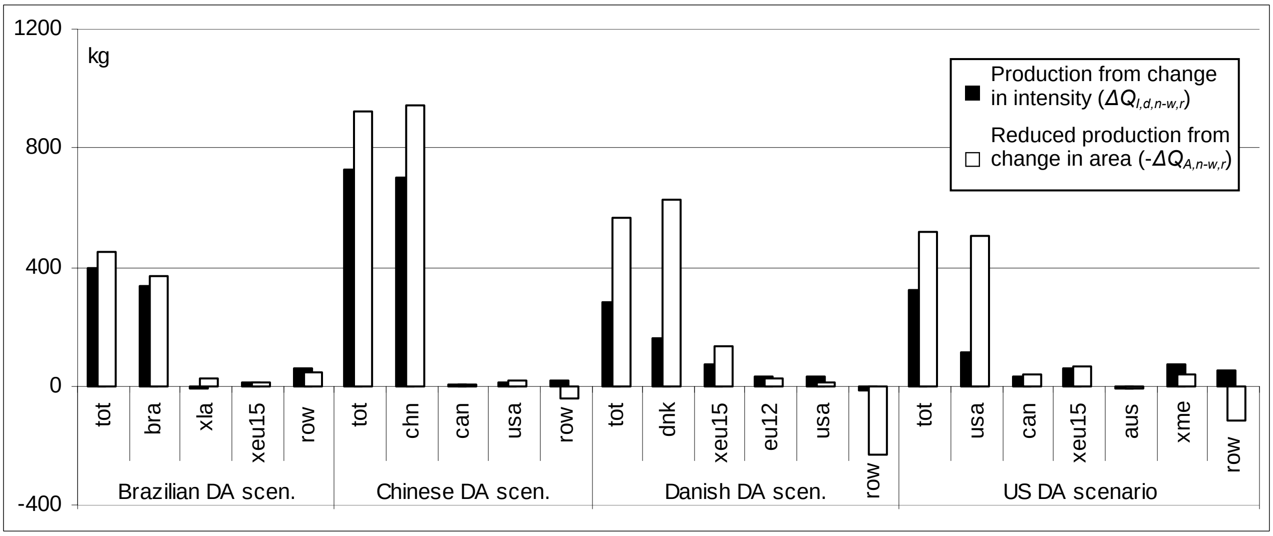


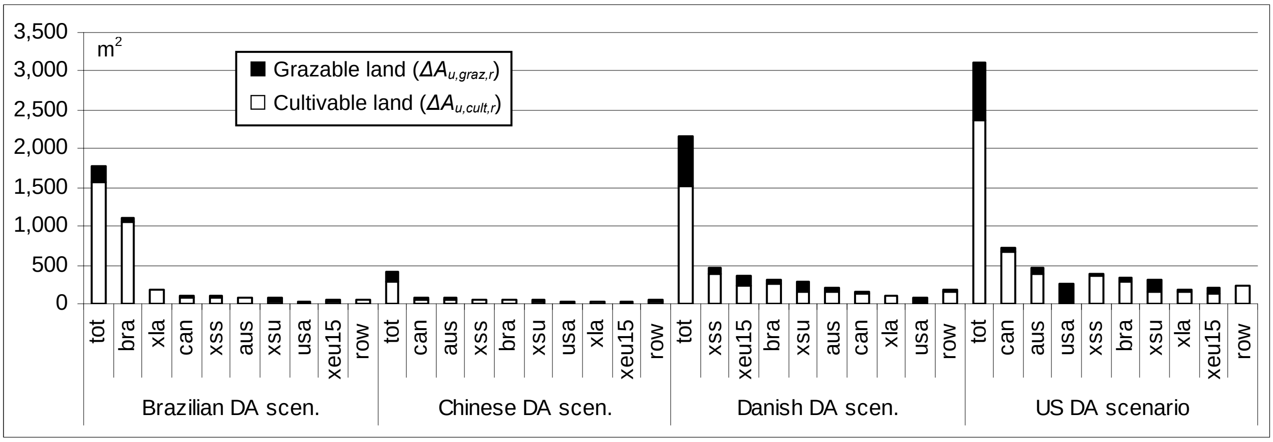




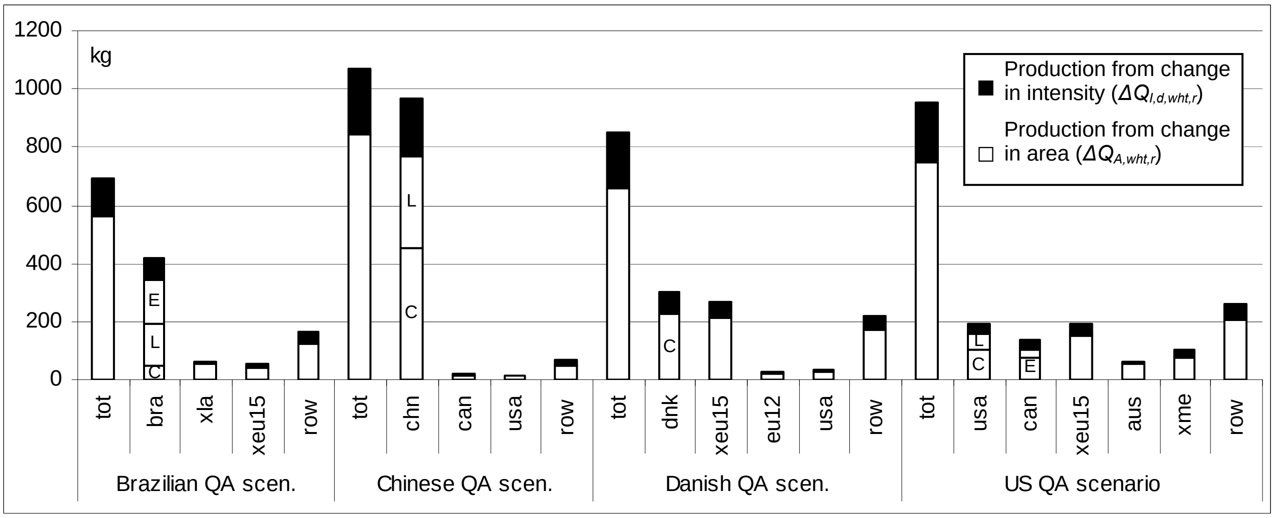
24 Appendix 11: Double Armington (DA) Scenarios

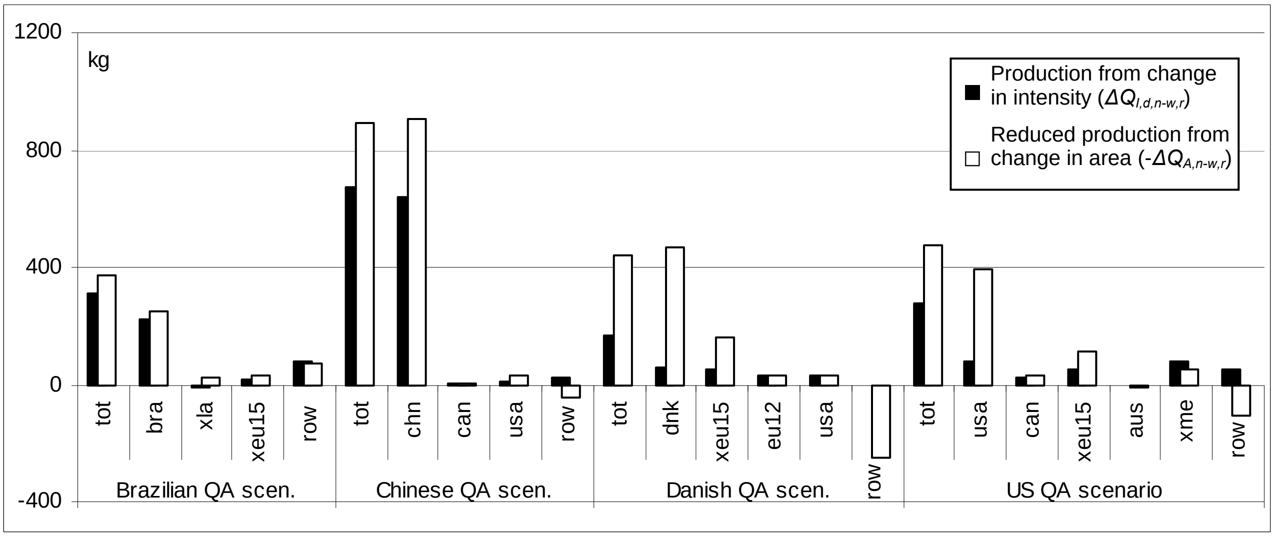


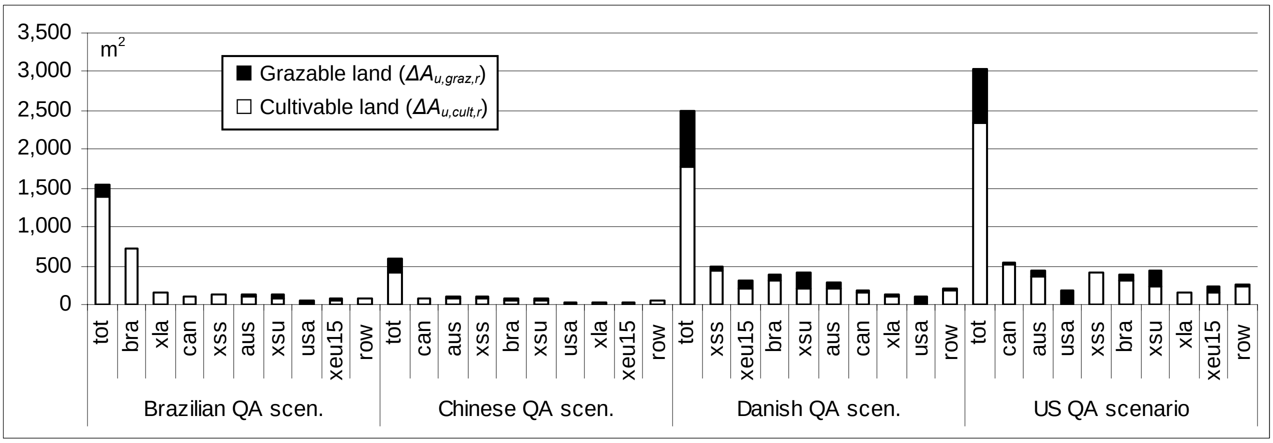




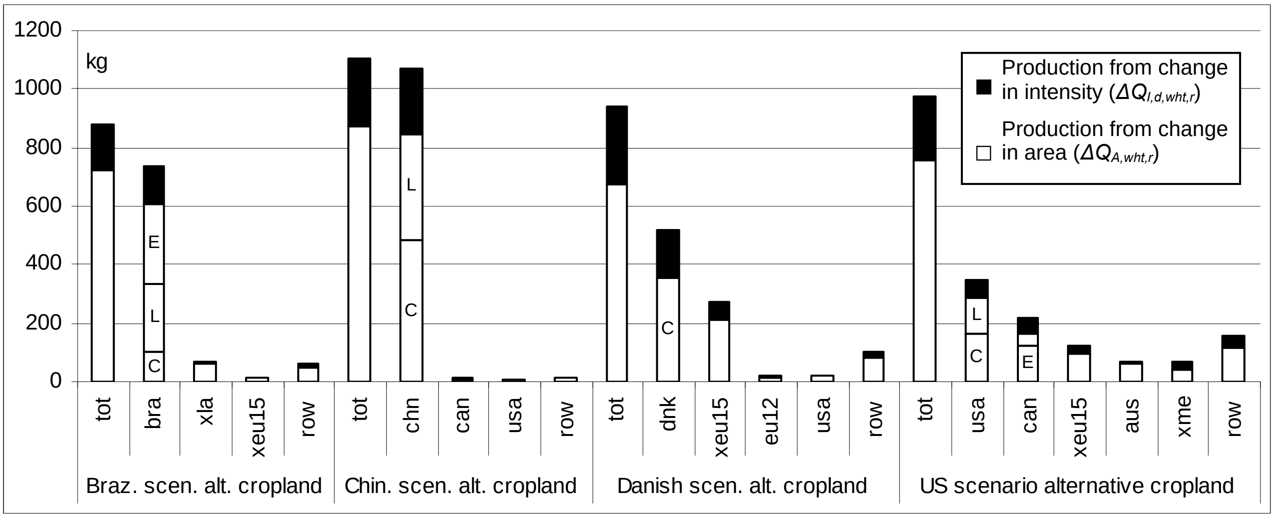
25 Appendix 12: Quadruple Armington (QA) Scenarios

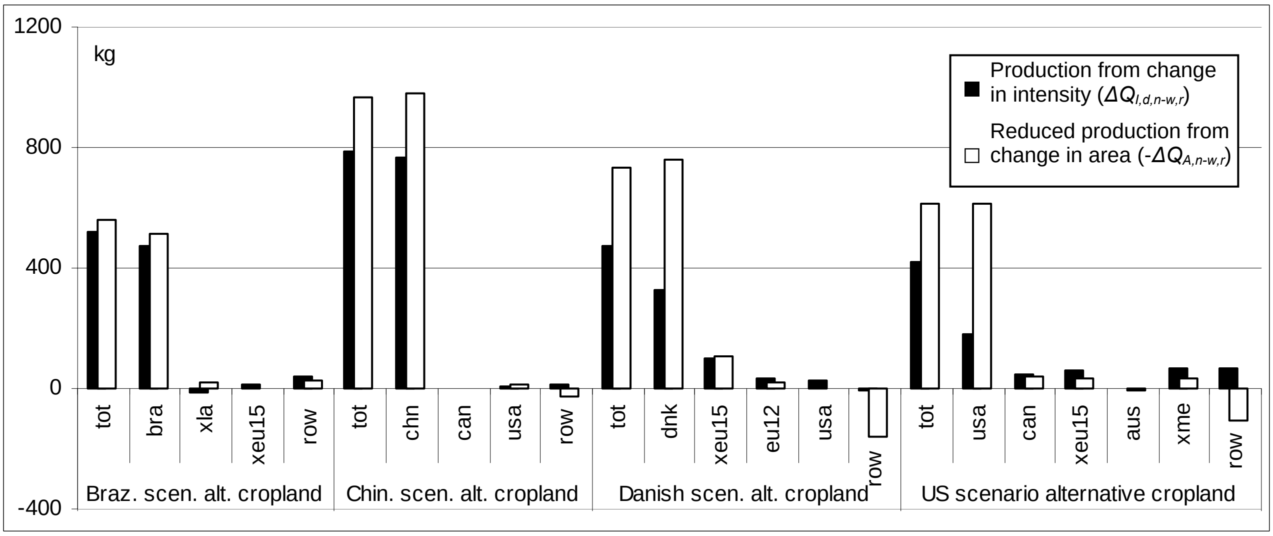


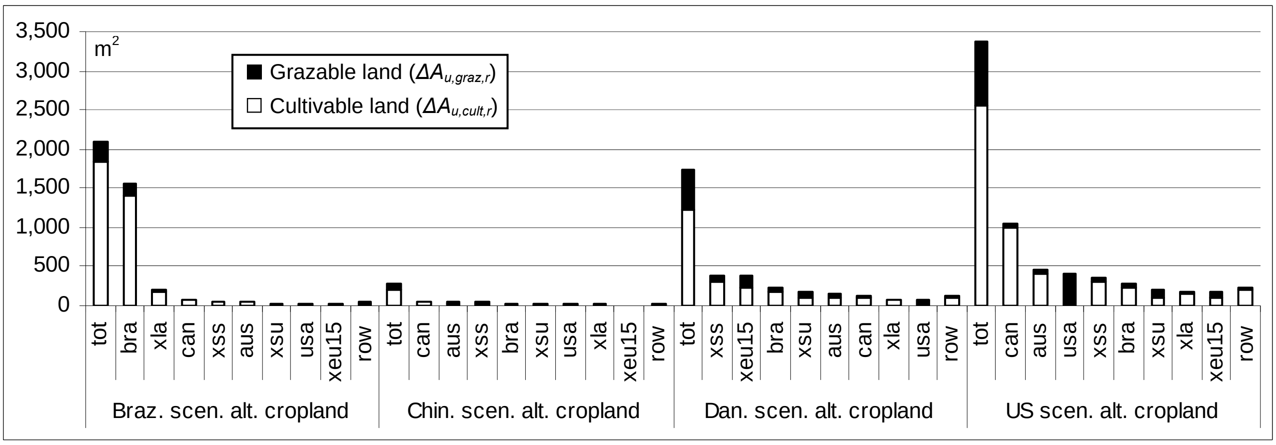




26 Appendix 13: Scenarios with Alternative Cropland Area







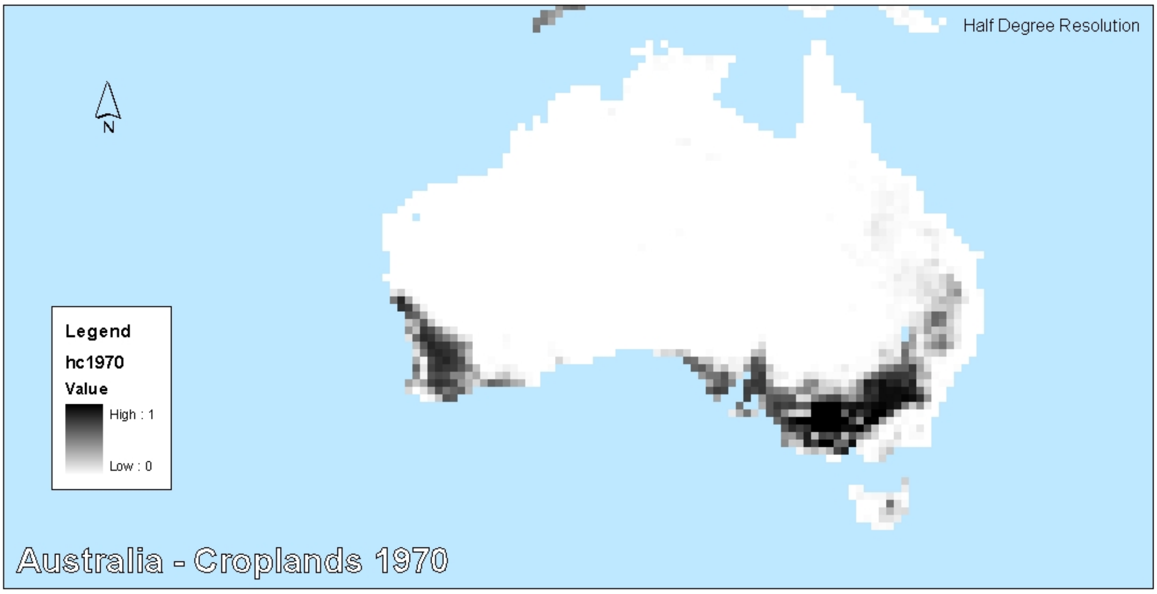
27 Appendix 14: Assumption 2 on Land Type Utilisation Trends

Assumption 2 in Section 5.1 states that if a region's cropland and pasture areas are both increasing, the utilisation trend for both cultivable and grazable land is positive. This assumption is supposed to be valid because the only two possible exceptions are highly theoretical and not very likely. These exceptions are discussed below.

1. If cultivable land is being converted from pasture to nature at a given rate but simultaneously from pasture to nature at a higher rate, then croplands will be increasing while the utilisation of cultivable land is decreasing. If grazable land from nature is then being converted to pastures at a higher rate than the conversion of pastures to cropland (on cultivable land), then the trend for both croplands and pastures will be increasing although utilisation of cultivable land is falling. However, it would not make sense to replace good cultivable land with less fertile grazable land in a scenario where the demand for both crops and livestock is increasing.

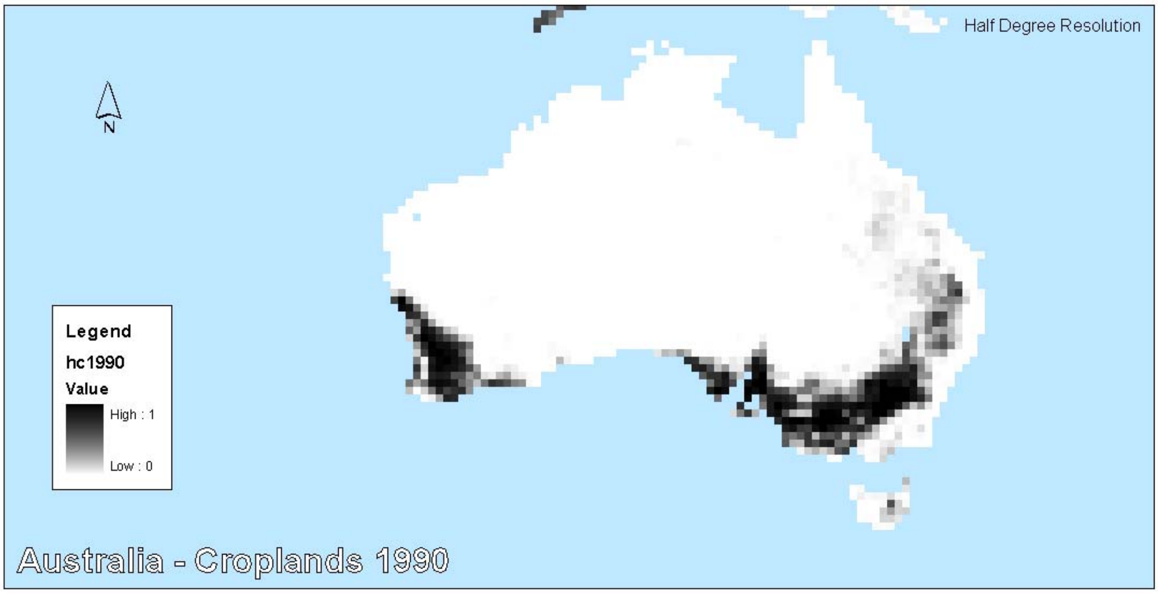
2. The utilisation of grazable land may be unaffected by an increase in cropland and pastures. That is, if this increase is only coming from cultivable land. However, it is highly unlikely that an increase in pastures would occur without an increase in the utilisation of grazable land – unless all grazable land is already utilised. This has only been observed for regions, which are also utilising all of their cultivable land, e.g. Denmark and China. In such regions, no expansion occurs, so they are not relevant in the analysis of biomes affected by agricultural expansion.

28 Appendix 15: Cropland Maps for Australia



Ramankutty N and Foley JA (1999): Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global Biogeochemical Cycles, Vol. 13, No 4, pages 997-1027, December 1999, Climate, People, and Environment Program (CPEP), Institute for Environmental studies, University of Washington, Madison.

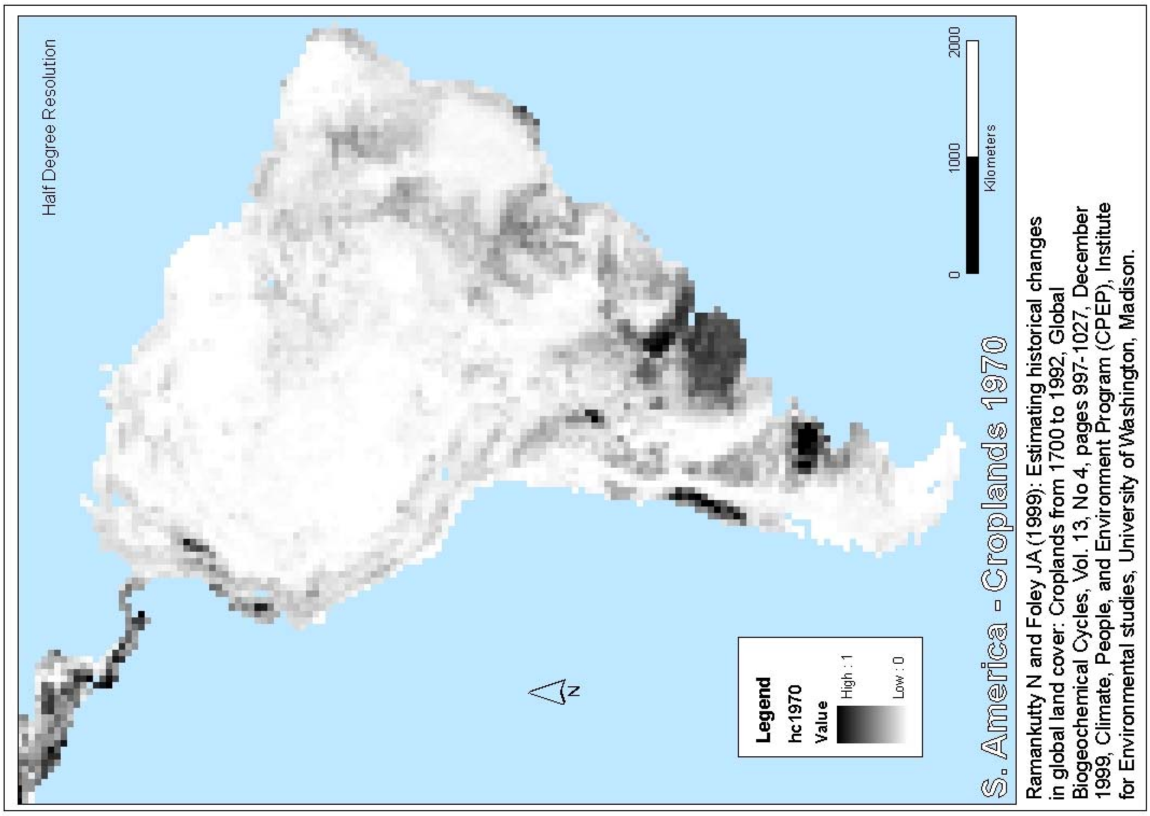
0 600 1200
Kilometers

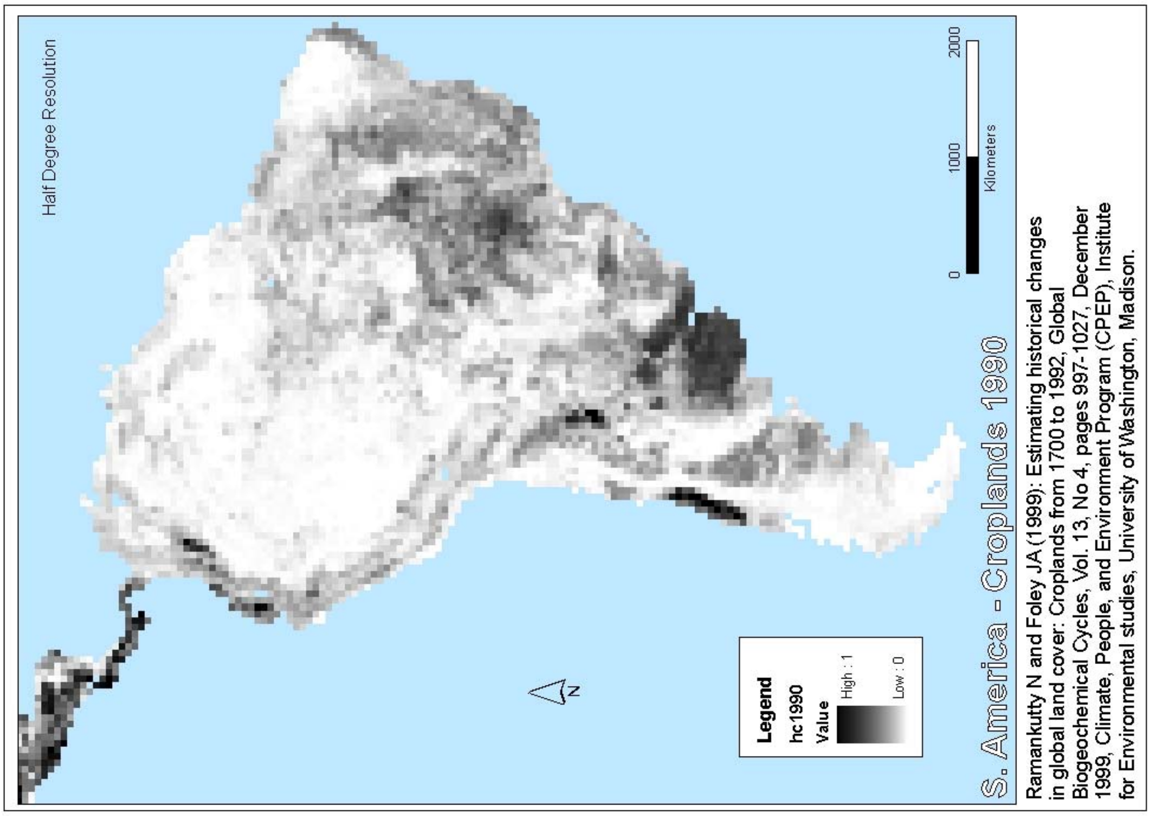


Ramankutty N and Foley JA (1999): Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global Biogeochemical Cycles, Vol. 13, No 4, pages 997-1027, December 1999, Climate, People, and Environment Program (CPEP), Institute for Environmental studies, University of Washington, Madison.

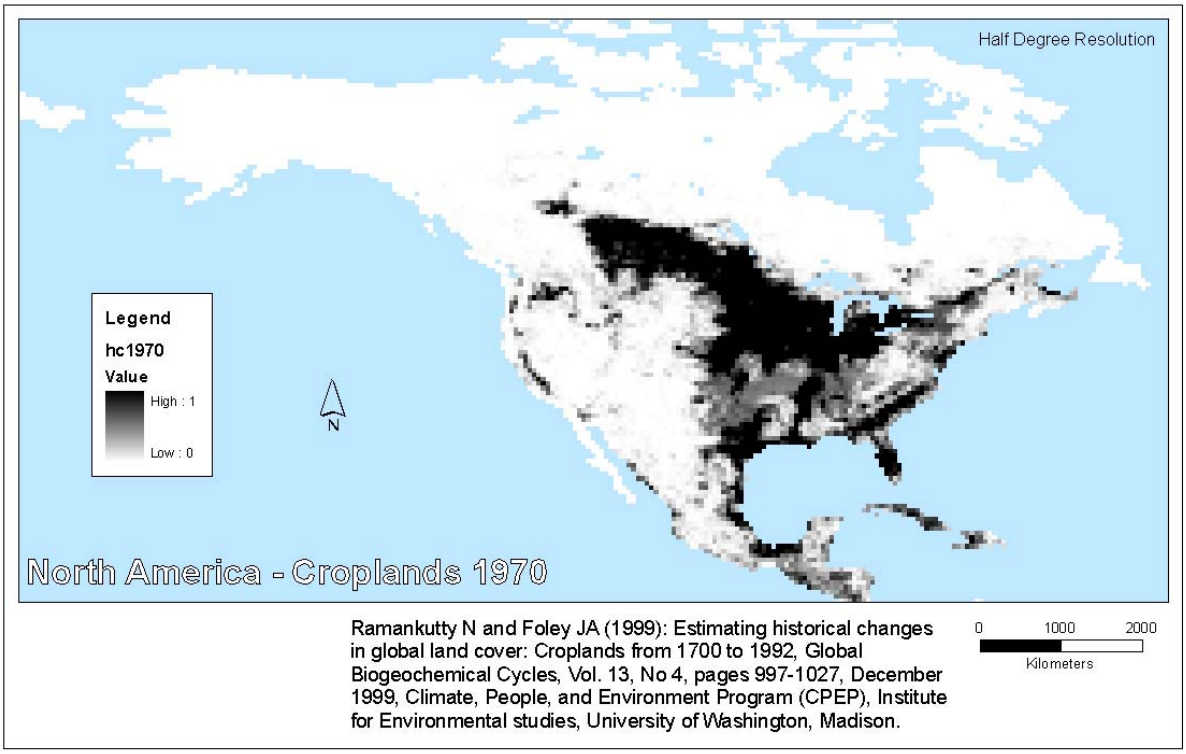
0 600 1200
Kilometers

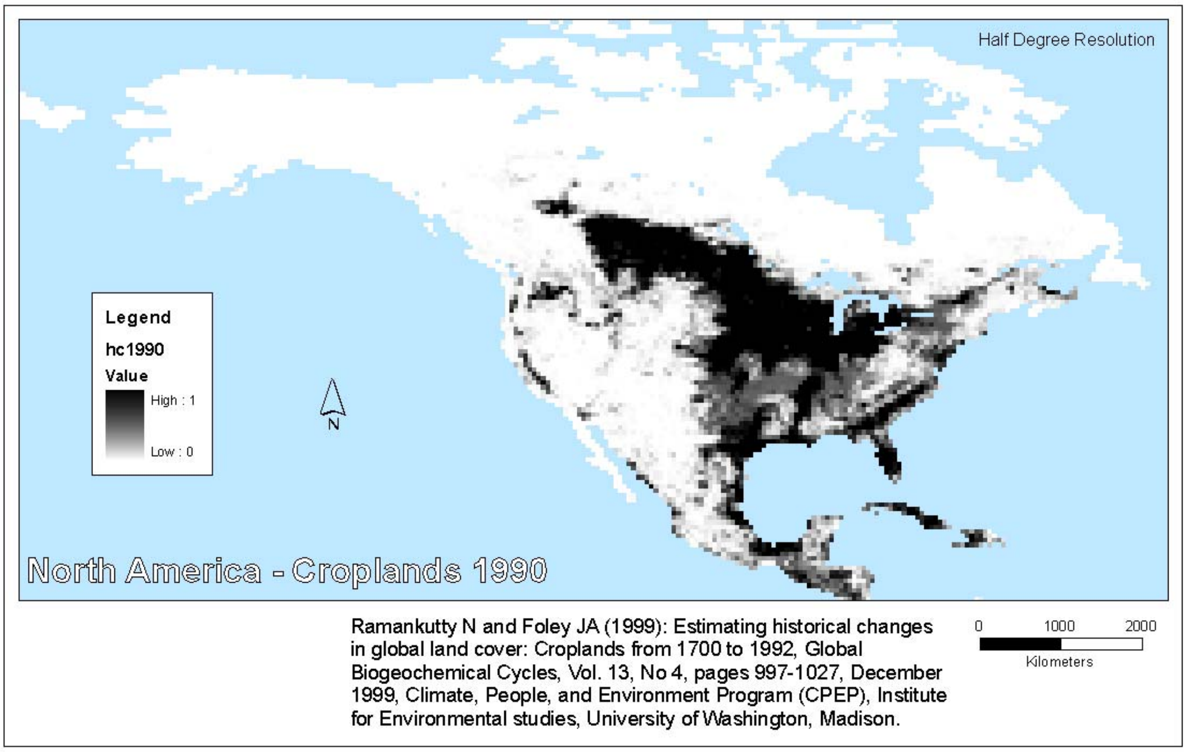
29 Appendix 16: Cropland Maps for South America



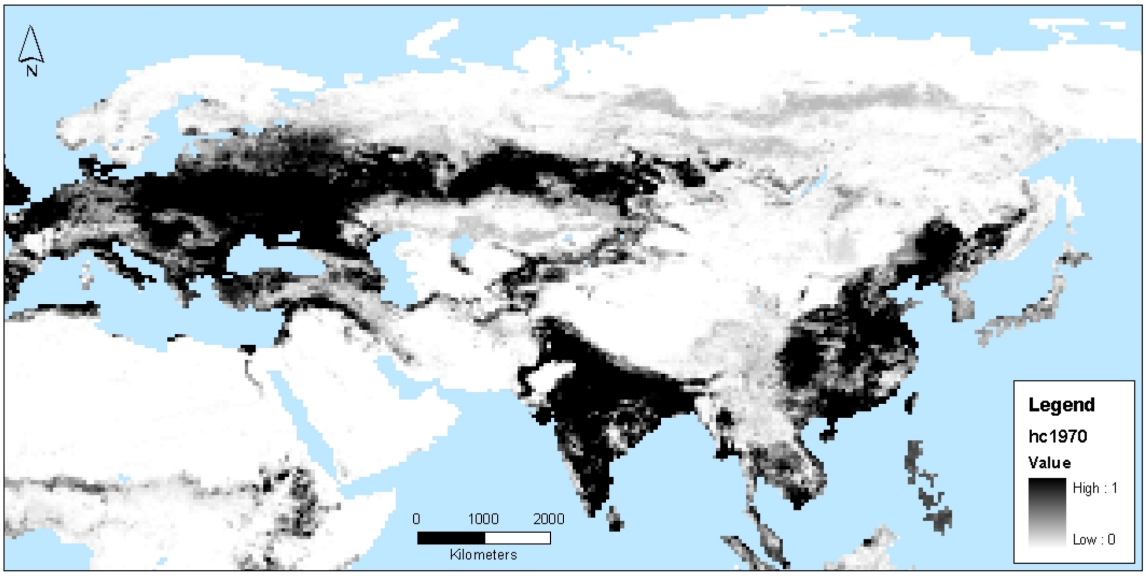


30 Appendix 17: Cropland Maps for North America



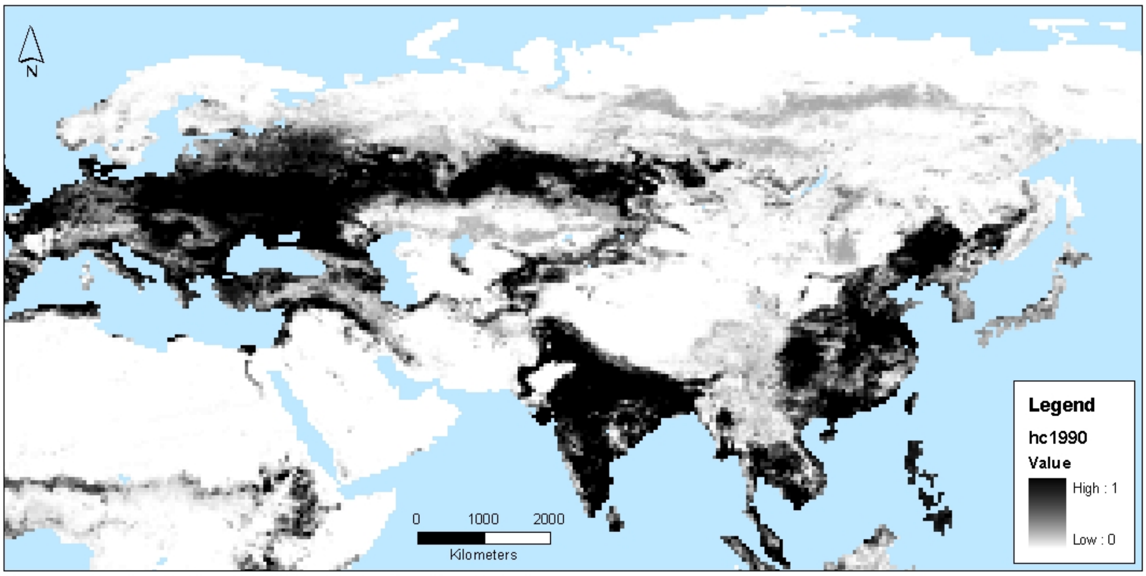


31 Appendix 18: Cropland Maps for Asia



Ramankutty N and Foley JA (1999): Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global Biogeochemical Cycles, Vol. 13, No 4, pages 997-1027, December 1999, Climate, People, and Environment Program (CPEP), Institute for Environmental studies, University of Washington, Madison.

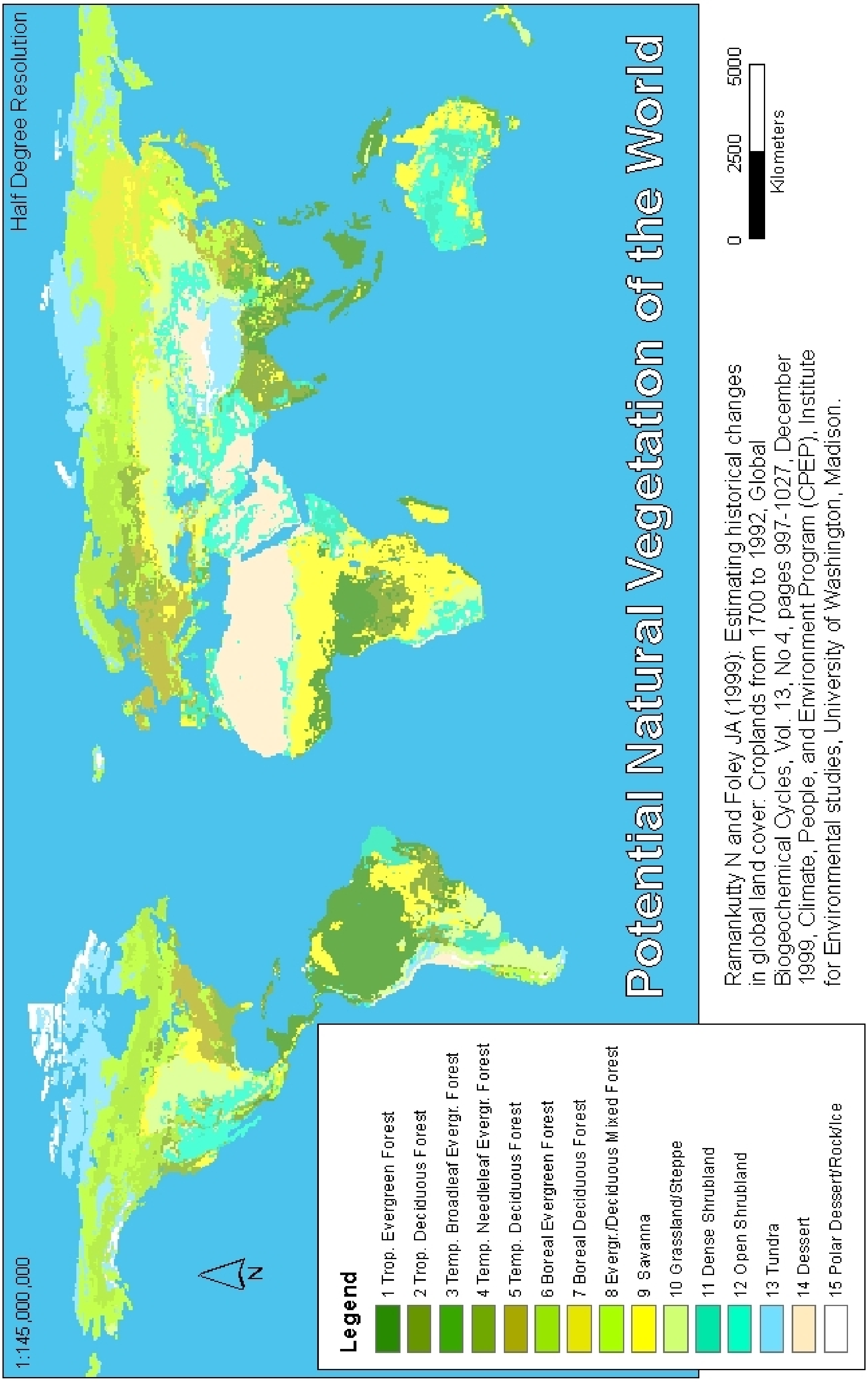
Asia - Croplands 1970



Ramankutty N and Foley JA (1999): Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global Biogeochemical Cycles, Vol. 13, No 4, pages 997-1027, December 1999, Climate, People, and Environment Program (CPEP), Institute for Environmental studies, University of Washington, Madison.

Asia - Croplands 1990

32 Appendix 19: Biome Map



33 Appendix 20: Conference on Land Use Implications of Biofuels

Kløverpris J, Wenzel H, Banse M, Milà i Canals L, Reenberg A (2008): *Conference and Workshop on Modelling Global Land Use Implications in the Environmental Assessment of Biofuels*. International Journal of Life Cycle Assessment 13 (3) 178–183, not peer reviewed.

Global Land Use Implications of Biofuels: State-of-the-Art

Conference and Workshop on Modelling Global Land Use Implications in the Environmental Assessment of Biofuels

Jesper Kløverpris[1,2]*, Henrik Wenzel[3], Martin Banse[4], Llorenç Milà i Canals[5] and Anette Reenberg[6]

[1] Technical University of Denmark, Department of Management Engineering, Section for Innovation and Sustainability, Produktionstorvet, Building 424, 2800 Lyngby, Denmark
[2] Novozymes A/S, Sustainability Development, Krogshøjvej 36, 2880 Bagsværd, Denmark
[3] University of Southern Denmark, Institute of Chemical Engineering, Biotechnology and Environmental Technology, Niels Bohrs Allé 1, 5230 Odense M, Denmark
[4] Agricultural Economics Research Institute LEI – Wageningen UR, PO Box 29703, 2502 LS The Hague, The Netherlands
[5] Centre for Environmental Strategy, University of Surrey (D3), GU2 7XH Guildford, Surrey, UK;
Current address: Unilever – Safety & Environmental Assurance Centre, Colworth Park, MK44 1LQ, Sharnbrook, Bedfordshire, UK
[6] University of Copenhagen, Department of Geography and Geology, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark

* **Corresponding author** (jklp@novozymes.com)

DOI: http://dx.doi.org/10.1065/lca2008.03.381

Please cite this paper as: Kløverpris J, Wenzel H, Banse M, Milà i Canals L, Reenberg A (2008): Conference and Workshop on Modelling Global Land Use Implications in the Environmental Assessment of Biofuels. Int J LCA 13 (3) 178–183

Participants in the full event:
Group 1 (land use): John Beghin, Alessio Boldrin, Ingmar Jürgens, Ruben Lubowski, Jim Lynch, Llorenç Milà i Canals, Kjeld Rasmussen, Guido Reinhardt, Silvia Secchi, Bo Weidema, Rainer Zah
Group 2 (land use): Riina Antikainen, Mark Delucchi, Erik Steen Jensen, Freddy O. Nachtergaele, Yolanda Lechon Perez, Anette Reenberg, James Schepers, Ashbindu Singh, Peter Verburg, Henrik Wenzel
Group 3 (land use): Martin Banse, Christof Walter, Lew Fulton, Anton Haverkort, Sebastien Haye, Matt Johnston, Marianne Jönsson, Jesper Kløverpris, Huey-Lin Lee, Martin Persson, Rüdiger Schaldach
Group 4 (social aspects): Roland Clift, Pamela del Canto, Uwe Fritsche, Shabbir H. Gheewala, Michael Hauschild, Andreas Jørgensen, Eric Lambin, Markku Lehtonen, Gregory Norris, Peter Poschen, Dan van der Horst

Abstract

Background, Aims and Scope. On 4–5 June 2007, an international conference was held in Copenhagen. It provided an interdisciplinary forum where economists and geographers met with LCA experts to discuss the challenges of modelling the ultimate land use changes caused by an increased demand for biofuels.

Main Features. The main feature of the conference was the cross-breeding of experience from the different approaches to land use modelling: The field of LCA could especially benefit from economic modelling in the identification of marginal crop production and the resulting expansion of the global agricultural area. Furthermore, the field of geography offers insights in the complexity behind new land cultivation and practical examples of where this is seen to occur on a regional scale.

Results. Results presented at the conference showed that the magnitude and location of land use changes caused by biofuels demand depend on where the demand arises. For instance, mandatory blending in the EU will increase land use both within and outside of Europe, especially in South America. A key learning for the LCA society was that the response to a change in demand for a given crop is not presented by a single crop supplier or a single country, but rather by responses from a variety of suppliers of several different crops in several countries.

Discussion. The intensification potential of current and future crop and biomass production was widely discussed. It was generally agreed that some parts of the third world hold large potentials for intensification, which are not realised due to a number of barriers resulting in so-called yield gaps.

Conclusions. Modelling the global land use implications of biofuels requires an interdisciplinary approach optimally integrating economic, geographical, biophysical, social and possibly other aspects in the modelling. This interdisciplinary approach is necessary but also difficult due to different perspectives and mindsets in the different disciplines.

Recommendations and Perspectives. The concept of a *location dependent marginal land use composite* should be introduced in LCA of biofuels and it should be acknowledged that the typical LCA assumption of linear substitution is not necessarily valid. Moreover, fertiliser restrictions/accessibility should be included in land use modelling and the relation between crop demand and intensification should be further explored. In addition, environmental impacts of land use intensification should be included in LCA, the powerful concept of land use curves should be further improved, and so should the modelling of diminishing returns in crop production.

Keywords: Biofuels, increased demand; economic modelling; expansion; geography; land use changes; LCA

Introduction

The increasing production of first generation biofuels[1] such as biodiesel and bioethanol leads to an increasing demand for crops, which can only be satisfied by cultivation of more

[1] Oil, sugar or starch harvested from 'useful' parts of agricultural crops (e.g. oil, seeds, grain) are converted to biodiesel via transesterification (oils) and to bioethanol via fermentation (starches and sugars) (Lynch).

land and/or intensification of the existing crop production. On the other hand, second generation biofuels[2] have the potential to decrease the pressure on land as long as they are produced from by-products such as straw or maize stalks (see e.g. Jensen and Thyø 2007). In order to determine the environmental consequences of an increasing demand for biofuels, it is necessary to identify the areas ultimately affected by the increased utilisation of biomass (world region and specific local ecosystem). Such land use changes depend on several factors, including market mechanisms, the availability of new cultivable land, yield improvement potentials, and socioeconomic conditions. As the list indicates, the identification of ultimate land use changes caused by biofuels requires inputs from several disciplines and is not likely to be solved by the LCA community alone. This acknowledgement was the basis for an international conference and workshop entitled 'Modelling Global Land Use and Social Implications in the Sustainability Assessment of Biofuels', which was a follow-up of a smaller workshop organised in 2006 (Milà i Canals et al. 2006). The event took place in Copenhagen (Denmark) on 4–5 June 2007 and the aim was to bring together scientists from economy, geography, and LCA to discuss the modelling of land use changes caused by biofuels. Furthermore, social implications of biofuels were discussed.

The first day of the conference consisted of an open plenary session with 14 presentations of which 12 addressed land use implications of biofuels. Approximately 40 scientists (including the speakers) were invited to take part in a wrap-up and discussion session in the evening. On the second day, these scientists gathered for a workshop consisting of four parallel break-out sessions with additional presentations from the group members followed by discussions of the conference themes. Three groups discussed land use and biofuels and one group discussed social aspects of biofuels. The outcome of the break-out sessions was reported in a final plenary session.

This paper presents the basic background for land use approaches within economics, geography, and LCA and summarises and synthesises the main findings of the conference with relevance for land use modelling. It focuses on the land use issue but all abstracts from the conference (including those on social implications) are available in Kløverpris (2007) and the presentations are available at www.biofuel assessment.dtu.dk; they are referred to with the surname of the presenter only.

1 General Approaches to Land Use Modelling

Before the presentation of the results and the synthesis of the conference, a brief introduction is given to the approaches to land use modelling within the three scientific disciplines, economics, geography, and life cycle assessment.

[2] Plant cells from any source (e.g. straw, wood) are broken down via acid hydrolysis or enzymes to release sugars that are then fermented to produce bioethanol. Alternatively syngas (hydrogen and carbon monoxide) is produced which can then be turned into synthetic diesel via Fischer Tropsch process (Lynch).

1.1 The economic approach

The economic models of interest in this context represent the economy with a number of geographical regions, each containing a number of sectors. Partial and general models represent respectively part of the economy (e.g. the agricultural sectors) and the entire economy. The interplay between sectors and regions is determined by so-called elasticities expressing the relative change in one variable caused by the relative change in another variable. For instance, a 10 percent increase in the price for wheat in a given region may cause the wheat production to increase by 8 percent. Besides the elasticities, the models build on a wealth of other data types, e.g. tariff rates, production volumes, and data on existing trade flows.

An economic model represents an economic equilibrium (supply equals demand). A change in the economy (e.g. increased crop demand) can be studied by adjusting the relevant model parameters to simulate the change of interest. The model then adapts to the new conditions by establishing a new economic equilibrium. This adaptation is driven by price signals resulting in production changes in the different sectors. If the agricultural sectors are affected, changes in the use of land are also likely to occur. However, only some economic models include agricultural land utilisation as a variable. This variable may be determined by so-called land supply curves expressing the regional relationships between land price and land supply. Land supply curves are based on estimates of the land potentially available for production. However, not only land availability should be included in economic models, but also land heterogeneity. Therefore, some of the more advanced economic models rely on detailed biophysical and climatic information to determine land constraints. For instance, Birur et al. (2007) use agro-ecological zones (AEZs) in combination with an exogenous land supply following the methodology outlined in Lee et al. (2005). Furthermore, the general equilibrium model LEITAP (Klijn and Vullings 2005) is linked to the ecological-environmental modelling framework IMAGE (Alcamo et al. 1998) allowing feedbacks of biophysical constraints and the use of detailed heterogeneous information such as land productivity.

To model land use changes caused by biofuels, it is not enough to incorporate an endogenous land supply variable in the economic models. In addition, biofuels must be included in the economic models as commodities or as blends with fossil fuels in petrol. Therefore, economic researchers throughout the world are discussing various approaches to include first and/or second generation biofuels in their quantitative models. This requires incorporation of detailed links between the energy sector and agricultural activities and factors, especially agricultural land use. Some outcomes of these ongoing efforts were presented at the conference (see Section 3).

1.2 The geographical approach

The geographical approach to land use systems (incl. monitoring and modelling hereof) aims at establishing a general understanding of land use dynamics, land use patterns, and land use driving forces. It corresponds well with land systems research in its most comprehensive form, which joins the human, environmental, and geographical information-remote sensing sciences in a discipline that seeks to improve:

- observation and monitoring of land changes underway throughout the world
- understanding of these changes as a complex coupled human-environment system
- spatially explicit modelling of land use and land cover change

There is a wide range of different geographical models. Recent decades' advances in remote sensing have contributed significantly with appropriate documentation of land cover at both local and global scale. Although considerable attention has been given to the spatial dynamics of land use, geographical models in general embrace a wide range of approaches such as spatial versus non-spatial; dynamic versus static; deductive versus inductive; agent based versus pixel-based; and global versus regional. An overview of the current practice in geographic modelling is presented by Verburg et al. (2004).

1.3 The LCA approach

In attributional LCA, the environmental assessment of biofuels is based on the direct suppliers of the necessary inputs to production. For instance, if ethanol is produced from European wheat, the land affected by biofuel production is assumed to be in Europe. Possible land constraints and displacement of other crops with its influence on land use elsewhere is thereby ignored. Furthermore, co-products are handled by allocation in attributional LCA. This means that the environmental impacts from biofuels production are simply split between the fuel and the co-products. It is thereby ignored that by-products from biofuels production often displace animal feed, which reduces the net pressure on land.

In consequential LCA, market mechanisms are taken into account and co-products are handled by system expansion. In principle, this means that all consequences of the change being studied (e.g. increased consumption of biofuels) are taken into account. Part of this procedure is to identify the marginal (as opposed to the direct) suppliers of inputs to production, i.e. those suppliers ultimately affected by changes in demand (Weidema 2003). Furthermore, the influence of co-products (e.g. displacement of animal feed) is included in the system modelling (Ekvall and Weidema 2004). It is typically assumed that the marginal suppliers have a single origin, e.g. a technology, country, or region.

2 Aspects of Importance for Modelling of Ultimate Land Use Induced by Biofuels Demand

Although consequential LCA, as a concept, is well suited for assessing the environmental impacts of an increased demand for biofuels, the practical application of the methodology still faces some challenges when it comes to identifying the land ultimately affected by increased biofuels production. Some of these issues are discussed in Kløverpris et al. (2008), a draft version of which was distributed prior to the conference to guide and inspire the debate on its most essential aspects:

Displacement-replacement mechanisms: When one crop displaces another, it is likely that the other crop (or a substitute) will be produced somewhere else thereby replacing the production lost due to the initial displacement. These dynamics are designated the displacement-replacement mechanisms.

Linear substitution: When a crop is displaced, an inherent feature of the LCA concept is to assume that it is fully replaced by production elsewhere. The replacement is based on functionality (e.g. nutritional value in case of animal feed products) and designated linear substitution.

Perfectly elastic supply: The increase in the production (supply) of a commodity caused by an increase in the price of that commodity is expressed by the supply elasticity. If consumption of a given product leads to an equivalent increase in production without affecting the rest of the market, the supply of that product is characterised as being perfectly elastic. The concept of linear substitution as well as LCA in general is based on an inherent assumption of products being in perfectly elastic supply. For instance, it is typically assumed that an increased use of biofuels will lead to an equivalent increase in crop production without affecting any other sectors using crops.

Diminishing returns: The crop yield per hectare is not proportional to the inputs to production (e.g. fertilisers). The more inputs applied to the field, the less is the additional increase in yield. This is characterised as diminishing returns.

Marginal crop production: The change in total crop production caused by a change in demand is designated marginal crop production. Changes in crop production happening independently of demand changes are not included.

3 Selected Results from Presentations

Kløverpris used a general equilibrium model to estimate the global agricultural expansion caused by a marginal increase in wheat consumption (as an example of increased crop demand caused by biofuels). Results demonstrated that the size of the global expansion heavily depends on where the wheat consumption takes place.

A general equilibrium model was also applied by Banse to show that agricultural land use within as well as outside the EU increases if mandatory blending is introduced. This expansion occurs especially in South America and might cause a decline in biodiversity in the countries affected.

Lee showed how agro-ecological zones (AEZs) can be incorporated in economic modelling to project the potential for GHG mitigation in agriculture and forestry. Her analysis shows that biophysical and economic land characteristics create comparative abatement advantages for land endowments.

Schaldach applied the spatial land use model LandShift for India to analyse the impact of biofuel crop production on land use at regional level. This analysis starts from a hypothesis that the cultivation of energy-crops will have a growing importance for India to fulfil the future energy demand. The first findings of this analysis identify a significant impact of bio-energy production on the spatial land-use pattern in India.

Verburg presented results based on the spatial land use model CLUE, which models geographic consequences. Results show that, in Europe, an enhanced production of biofuel crops will lead to less abandonment of cropland. However, cultivation is concentrated in a number of large regions with well-developed infrastructure and large areas of suitable arable land. These potential 'hotspots' of biofuel crop cultivation include NE Germany, parts of Poland, Lithuania, Czech Republic, agricultural areas around Paris, and around the border area of Slovakia, Hungary and Austria.

4 Selected Results from Break-out Sessions

It was generally agreed that an interdisciplinary approach to the modelling of land use changes caused by biofuels is necessary. Actually, it was mentioned that even more disciplines should have been represented at the conference, such as soil science and agronomy. Furthermore, it was stated that although we should strive to model the land use implications of biofuels, we should use models wisely by accepting their limitations and interpreting results with care. It was also pointed out that the models need to be transparent in order to use them in LCA.

Group 2 characterised the land supply curves used in some economic models (Kløverpris, Banse) as a powerful concept although problems with the calibration exist. Furthermore, the suitability of the agricultural land expressed by the land supply curves is not the only decisive factor. Infrastructure and social aspects also determine which land is the next to be used.

The ability of models to handle diminishing returns in crop production was also discussed. Apparently, this issue is taken into account by, at least, some models but only in a very general manner. There seems to be room for improvement concerning the algorithms and values used to model the correlations between input factors and yield.

Intensification and its interdependency on expansion was one of the main issues discussed. It was generally agreed that some regions in the third world hold large potentials for intensification, which are not realised due to a number of barriers in terms of local resource constraints (e.g. water and phosphorous) as well as no or low access to capital, knowledge, fertilisers, and markets. The lack of know-how leads to suboptimal crop yields seen in relation to the input of agricultural resources (water, fertilisers, pesticides etc.). This creates a yield gap (**Fig. 1**). Johnston is currently working on a quantification of the increased agricultural production that could be achieved if such yield gaps were closed.

Geographical differences influencing intensification were also discussed. Environmental legislation in the EU restricts the

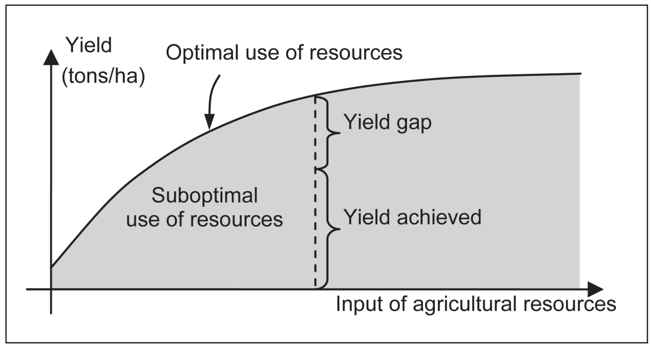


Fig. 1: Conceptual illustration of optimal use (the curve) and suboptimal use (the grey area) of agricultural resources and an example of a yield gap

use of fertilisers, which means that higher crop prices will not result in higher yields achieved with more fertilisers. This is different in the US where a recent doubling of the corn price has changed the economic optimum of fertiliser inputs and, thereby, increased yields per hectare. These legal aspects must be accounted for in the modelling of land use changes.

Group 3 debated the trade-offs between expansion and intensification. Whereas expansion has negative impacts on natural habitats and thereby biodiversity, intensification may lead to other environmental impacts like eutrophication. To assess the environmental sustainability of biofuels, it is therefore necessary to determine the relationship between expansion and intensification caused by biofuels production and include it in the modelling of land use changes.

As to whether the increased demand for biofuels will lead to intensification by technological development in the form of improved crop strains, it was suggested that the biofuel demand may cause a new green revolution in which non-food GM crops are developed for rapid intensification to provide feedstock for biofuel production. Furthermore, the use of aquaculture was mentioned as a potential source of biomass. Algae in reservoirs can produce more biomass per hectare than land based crops and may even be a potential sink for CO_2.

In relation to the use of agricultural residues, it was stressed that only a certain share of this biomass resource can be removed from the soil if the fertility is to be maintained; this amount depends on local conditions. It was recommended to include soil carbon in the modelling of land use consequences derived from biofuel production (Milà i Canals).

5 Synthesis

Based on the results and discussions at the conference, we synthesise the findings relevant for life cycle inventory modelling of land use caused by the increased demand for biofuels.

5.1 Boundary conditions for the system modelling

The scale of the recent increase in the demand for biofuel raw materials (biomass) is large and the geographical scope is global (Beghin, Banse, Singh). This must be taken into account in the environmental assessment of the increased biofuels production. The scale itself has implications for the (marginal) suppliers responding to the new crop demand (Kløverpris, Banse, Beghin, Lambin). Moreover, due to the fact that crop markets are international and crops substitute each other within groups of similar chemical composition/nutritional value, increased demand for one crop influences the demand and supply on crop markets in general through the displacement-replacement mechanisms (Kløverpris, Beghin, Banse, Wenzel 2). Modelling the response to an increased demand for one crop therefore requires identification of other crops affected. At the conference, it became evident that many other crops in many regions of the world might be influenced when prioritising crops for biofuels in one country (Kløverpris, Beghin, Banse).

With respect to time scale, prioritising production of biofuels has implications for at least several decades, acknowledging the payback of investments in production facilities. In order to generate a solid platform for investments and for biofuel markets, the incentives generated must be kept robust for a longer period thereby implying a longer term prioritisation of crops for biofuels. To some extent we thereby luck ourselves into this crop prioritisation and biomass conversion pathway for several decades (Clift). This has implications for how we should model the consequences, in case biomass and land is constrained, because locking onto a certain technological pathway in this case means depriving ourselves the opportunity of using the same limited land or biomass in other technological pathways (Wenzel 1).

5.2 Biomass and land constraints

Biomass and land is of limited availability compared to the potential new customers for it being all sectors in society currently depending on fossil fuels (Wenzel 1, Reinhardt). The potential magnitude of biomass demand from these sectors is many times bigger than the current agricultural production. Today, agriculture is essentially producing food, and the energy content of foodstuffs consumed by the world's population is only around 6% of the energy content of the fossil fuels consumed by the world's population (Wenzel 1). As the growth in consumption of both food and energy is today higher than agricultural yield increases, increased crop demand is likely to result in new land cultivation but, according to Ramankutty et al. (2002), the current upper limit for new land cultivation is around a doubling (Wenzel 1). Much less than this can, however, be cultivated without transformation of protected natural areas (Delucchi, Wenzel 1). Any long term prioritisation of land and crops for one technological pathway will therefore happen at the expense of other uses of the same land and crop. The assessment of biofuels must therefore be seen in relation to alternative utilisation of biomass.

5.3 Marginal crop production

The conference demonstrated that even in some of the most advanced consequential LCAs, the approach to identifying marginal crop production is inadequate. When learning from the economic modelling, it seems clear that the assumption of a single most competitive supplier, in terms of a technology or region, does not hold true (see section 1.3). On the contrary, the changes in demand or supply of one crop influence the production of other crops in a variety of countries (Kløverpris, Beghin, Banse, Verburg, Wenzel 2). The reason is that several suppliers will respond to changes in crop demand and that the relative contribution from the marginal suppliers due to tariffs, transportation costs and other trade barriers will depend on the geographical location from where the change in crop demand originates. All these factors determine the marginal land use response to increased biofuel demand. We therefore introduce the concept of a *location dependent marginal land use composite*, i.e. the sum of global agricultural land use expansion caused by biofuel demand originating from a specific location. This is one issue where the LCA society could benefit from economic modelling.

5.4 Linear substitution

Results presented at the conference indicated that the demand for biofuels will affect crop prices in more than just the short term (Banse, Beghin). This shows that the supply of crops is not perfectly elastic and that linear substitution (see section 2) cannot necessarily be assumed in the modelling of land use changes caused by biofuels. This is also an issue on which the LCA society could learn from economic modelling.

5.5 Demand driven intensification

When striving to follow the displacement-replacement flows, a key uncertainty factor is the role of intensification (Wenzel 2). It was widely discussed at the conference, how much of the response to an increase in demand, one should attribute to intensification, i.e. increase in crop yields per hectare. Intensification partly occurs independent of demand (e.g. due to continuous competition) and partly due to price increases and R&D motivated by perceived threats and opportunities based on the development in demand (Wenzel 2). The conference did not result in any clear recommendations for how to handle the relation between demand and intensification in the modelling of land use changes caused by biofuels. This remains a crucial point for further clarification.

5.6 Contributions from the field of geography

The field of geography offers at least two important contributions to the modelling of land use changes caused by biofuels production. It provides spatially explicit datasets of land use and land cover, which can be used in the construction of land supply curves and in the assessment of the areas affected by increased cultivation of land. The geographical approach also offers an understanding of land use dynamics, which goes beyond the neoclassical supply and demand mechanisms. This insight can also help to refine predictions of land use changes caused by biofuels.

6 Conclusions

In order to carry out life cycle assessments of biofuels, there is a need for modelling of the related land use consequences. So far, the general LCA approach to land use modelling has been based on functionality of products and by-products and an implicit assumption of linear substitution. In consequential LCA, the ambition is to identify marginal suppliers of the crops affected by biofuel consumption. However, the methodology needs further refinement. The economical approach is based on price signals caused by the demand for biofuels. The increasing prices lead to increasing production of biomass, which is achieved by a combination of intensification and expansion. In some economic models, the price of land is determined by land supply curves and thereby factored in. The geographical approach is broader combining human, environmental, and geographical information-remote sensing sciences with the aim of establishing a general understanding of land use dynamics, land use patterns and land use driving forces. The modelling of land use consequences of biofuels requires an interdisciplinary approach optimally integrating economic, geographical, biophysical, social and possibly other aspects in the modelling. This approach is necessary but also a challenge due to different perspectives and mindsets in the different disciplines.

It was generally agreed that there is a huge intensification potential if agricultural inputs were used optimally and third world countries had better access to the world market. This means that biomass production can be increased significantly without further expansion of the agricultural area. However, the intensification of land use may have other consequences, e.g. loss of soil carbon and increased leaching of nutrients, which should be taken into account in the environmental assessment.

The land supply curves applied in some economic models constitute a powerful concept in land use modelling although the calibration of the curves could still be improved. Likewise, the ability of economic models to handle diminishing returns in crop production also holds room for improvement.

As for environmental modelling (LCA), the concept of a *location dependent marginal land use composite* should be introduced as an expression for the sum of agricultural land use expansion caused by biofuel consumption in a given location. Furthermore, the implicit assumption of linear substitution typically applied in LCA should also be reconsidered as the supply of biomass is not perfectly elastic. Economic models can be helpful in this aspect.

It is recommended to incorporate (possibly more transparently) restrictions on the use of fertilisers as well as accessibility to fertilisers in the economic models. The clarification of the relation between demand and intensification also requires more research. Furthermore, the modelling of land use changes in a broader sense should build in constraints caused by scarcity of resources (e.g. land, water, and phosphorous) and take into account the value of ecosystem services (e.g. water filtration). Finally, models should be used wisely and not trusted blindly.

Acknowledgements. The authors would like to thank the OECD, Novozymes A/S, Unilever, and the Danish Institute for Product Development (IPU) for sponsoring the conference. Furthermore, thanks to all participants for their contributions and, finally, thanks to Alessio Boldrin, Thilde Fruergaard, Karsten Hedegaard Jensen, and Kathrine Thyø from Residual Resources Research (3R) at the Technical University of Denmark for practical help during the conference.

References

Alcamo J, Leemans R, Kreileman GJJ (1998): Global change scenarios of the 21st century. Results from the IMAGE 2.1 model. Pergamon & Elseviers Science, London

Birur DK, Hertel TW, Tyner WE (2007): The biofuel boom: implications for world food markets, paper presented at the Food Economy Conference, The Hague, October 18–19

Ekvall T, Weidema BP (2004): System boundaries and input data in consequential life cycle inventory analysis. Int J LCA 9, 161–171

Jensen KH, Thyø KA (2007): 2nd generation bioethanol for transport: the IBUS concept – boundary conditions and environmental assessment. Department of Manufacturing Engineering and Management, Technical University of Denmark, DK-2800 Lyngby, Denmark

Klijn JA, Vullings LAE (2005): The EURURALIS Study: Technical Document, EURURALIS 1.0 – A Scenario Study on Europe's Rural Areas to Support Policy Discussion. RIVM, Alterra-rapport 1196

Kløverpris J (ed) (2007): Pre-document. Abstracts, Programme and List of participants. Biofuels Assessment Conference 4–5 June, Copenhagen, Denmark. Department of Manufacturing Engineering and Management, Technical University of Denmark, ISBN 81-91035-61-9 <www.biofuelassessment.dtu.dk>

Kløverpris J, Wenzel H, Nielsen PH (2008): Life cycle inventory modelling of land use induced by crop consumption part 1: Conceptual analysis and methodological proposal. Int J LCA 13, 13–21

Lee H, Hertel TW, Sohngen B, Ramankutty N (2005): Towards An Integrated Land Use Data Base for Assessing the Potential for Greenhouse Gas Mitigation. GTAP Technical Paper, no. 25, Center for Global Trade Analysis, Purdue University

Milà i Canals L, Clift R, Basson L, Hansen Y, Brandão M (2006): Expert Workshop on Land Use Impacts in Life Cycle Assessment (LCA). 12–13 June 2006 Guildford, Surrey (UK). Int J LCA 11, 363–368

Ramankutty N, Foley JA, Norman J, McSweeney K (2002): The global distribution of cultivable land: current patterns and sensitivity to possible climate change. Global Ecology and Biogeography 11, 377–392

Verburg et al. (2004): Land use change modelling: current practice and research priorities. GeoJournal 61, 309–324

Weidema BP (2003): Market information in life cycle assessment. Danish Environmental Protection Agency, Danish Ministry of Environment. Environmental Project No. 863

The purpose of the present PhD project was to identify the mechanisms governing global land use consequences of increased crop demand in a given location and, based on this conceptual analysis, to present and demonstrate a method proposal for construction of land use data that can be used in life cycle assessments involving crop consumption.

Increased demand for a given crop can be met by intensification, expansion, and/or by displacement of other crops or pastures. The last option will reduce the supply of other agricultural products, which may then be replaced elsewhere. Such displacement-replacement mechanisms are governed by the availability of suitable agricultural land and several economic conditions, such as transport and trade costs. To estimate the land use response to an increase in crop demand, economic modelling can be used. In this project, the economic equilibrium model GTAP (Global Trade Analysis Project) was modified and applied to simulate increased demand for wheat in respectively Brazil, China, Denmark, and the USA. The net expansion of the global agricultural area was thereby estimated and it was attempted to classify the affected nature types (biomes) by use of global agricultural maps and agricultural statistics.

ISBN 978-87-90855-69-7

DTU Management Engineering
Department of Management Engineering
Technical University of Denmark

Produktionstorvet
Building 424
DK-2800 Kongens Lyngby
Denmark
Tel. +45 45 25 48 00
Fax +45 45 93 34 35

www.man.dtu.dk